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# Innovation, Interrupted—Next-Generation Surface-Combatant Design

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# INNOVATION, INTERRUPTED

## Next-Generation Surface-Combatant Design

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*The fact that efficient guns and gun-armed warships remained . . . a European specialty . . . is a strong indication that technology in itself was not enough. The society must also have the necessary flexibility and dynamism to absorb technology and change the institutional framework in order to make the best possible use of them.*

JAN GLETE, *WARFARE AT SEA, 1500–1650*

"Pearl Harbor changed everything" is the dramatic beginning to Douglas Smith's magisterial book on American World War II aircraft carrier battles in the Pacific theater. "During that difficult period, naval aviators sought to *reconfigure* the tactics, material, and equipment that had been developed during the prewar years for actual combat."[1] Contemporaneously, "[w]hen war broke out in Europe in 1939 it quickly became apparent that the large fleet actions for which the interwar destroyers had been primarily designed were unlikely to materialize."[2] And "[o]nce it became clear that the war in the Pacific would not be following its anticipated course . . . *modifications* became necessary in both the U.S. Navy and the [Imperial Japanese Navy]."[3] On 8 December 1941, the United States declared unrestricted submarine warfare against imperial Japan—a mode of warfare that both America and Great Britain long had considered immoral and unethical as a matter of formal diplomatic and naval policy.[4]

After fighting a global maritime war in World War I, how did the major naval powers in the 1920s and 1930s get the "next war" so wrong? Those navies engaged in years of intense interwar operational study and strategic thought and negotiated no fewer than four separate, technically prescriptive naval-arms-control treaties and agreements. How did they manage nonetheless to build new ships that required immediate *reconfiguration*

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and *modification* to fight the next maritime war, one they had long expected and anticipated?

I seek to answer that question with a blended analysis of technology, engineering, and maritime operations. First, I discuss the incremental prewar warship-design process that created the need for ships to be reconfigured and modified to the demands that World War II imposed—a process conceptually unchanged since the Elizabethan era. Next, I describe the two new and innovative warship-design methodologies—multimission and open-architecture approaches—that emerged just before and during the 1941–45 Pacific campaign that enabled American naval aviators and submariners to succeed, spectacularly, in new, unexpected operational environments. I then discuss the dissonance that the contemporaneous use of these three ship-design approaches created in the U.S. Navy's current ship-design and ship-sustainment processes. I conclude that the U.S. Navy must transition to a next-generation surface-combatant-design process that I term "*Enterprise* design," to accommodate today's—and the future's—dynamic and unpredictable war-fighting environment.

I illuminate the three warship-design philosophies by profiling three famous ships from the Pacific theater of World War II from both operational and technical perspectives. Interwar strategic and operational theories drove real engineering innovation and the development of key shipboard and weapon technical characteristics, but some of these designs could not then be adapted to new realities that were exposed by naval combat at the start of World War II. The sources of that inflexibility reach back to design philosophies that emerged in England during the years leading up to its face-off with the famous Spanish Armada of 1588. I then discuss postwar maritime and operational innovation through to the present day from a technological perspective, showing the growing, deleterious effects of those four-hundred-year-old ship-design principles, even as the merits of new approaches were being realized. Finally, I highlight Danish surface-ship-design innovation, uniquely grounded in this new approach, to examine historic and future USN surface-ship-design and -construction trends, closing with a proposal for an American surface-combatant "navy for the ages."

## A TALE OF THREE SHIPS

The effects of interwar mission uncertainty and technological innovation are illustrated best by profiling three ships designed in the 1930s that fought in the Pacific theater during the dramatic early months of America's involvement in World War II. The Japanese battleship *Yamato,* the U.S. submarine *Wahoo* (SS 238), and the aircraft carrier *Hornet* (CV 8) embody, respectively, traditional warship-design concepts and two new design concepts developed during the interwar years from operational experience in World War I. *Yamato* represents the iterative warship-design process that emerged during the Elizabethan era. In contrast, *Wahoo* demonstrated an innovative, new, multimission approach to that historic warship-design philosophy, while *Hornet*'s revolutionary, open-architecture design marked a complete break with prior practices.[5]

**Yamato: *Last Ship of the Elizabethan Way***

The Imperial Japanese Navy (IJN) battleship *Yamato* would have won every engineering and acquisition excellence award available in today's U.S. Navy. Lethal and survivable, it was designed to meet a clear, well-founded, well-established, analytically derived war-fighting requirement.[6] Its design incorporated several new and innovative battleship technologies; a main battery of record-breaking eighteen-inch guns, massive armor belts, and unprecedented horsepower and speed made *Yamato* arguably the most powerful battleship ever built. *Yamato* and its sisters were built on schedule and fully met all their combat-performance requirements on delivery to the fleet. As a bonus, *Yamato* was built in total secrecy; its subsequent appearance in battle was a complete surprise to the U.S. Navy.[7]

*Yamato* was delivered in 1941, just before Japan's attack on Pearl Harbor; its sister ship *Musashi* was delivered six months later; both were nominally on schedule. *Yamato,* alone, accounted for half of Japan's total new-warship construction tonnage delivered in 1941, and *Musashi* represented more than a third of its new-warship tonnage for 1942.[8] This one shipbuilding program clearly had the IJN's highest priority.

The Washington Naval Treaty of 1922's 3 : 5 : 5 ratio established an inferior number of battleships that Japan could maintain relative to the United States and Great Britain.[9] To comply with the treaty's terms, Japan quickly broke up or scrapped battleships sitting on shipways. When Japan abrogated both the Washington Treaty and the follow-on London Naval Treaty in 1936, it began a naval-rearmament plan from a position of profound relative weakness.[10] Japan did not have the industrial capacity to build up to parity in battleships with the United States; instead, it needed to build fewer but more-powerful new ships that could leapfrog established American naval strength. Since the United States had not built a new posttreaty fleet yet, Japan had to postulate what a future posttreaty American battleship would look like, then design and build a more powerful new class of ships to defeat that projected American design. *Yamato* was the result. The three planned *Yamato*-class ships were designed to defeat five of the imagined new U.S. battleships in a classic Mahan-inspired, mid-Pacific surface duel.[11]

Despite the excellence of its design, the power of its weapons, the precision of its war-fighting requirements, and the skill of its builders, *Yamato* and its sisters proved useless in the Pacific War that followed.[12] They sank no ships and won no

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battles; only *Yamato* ever even sighted an enemy ship.[13] Worse, their prodigious fuel consumption limited both their own and the rest of the IJN's fleet operations after naval-fuel supplies came under stress from U.S. commerce raids.[14]

At 73,000 tons, each *Yamato*-class battleship represented the industrial equivalent of two aircraft carriers, which, at that time, displaced about 37,000 tons (e.g., the *Taiho* class of 1942). After the Battle of Midway, a planned but unnamed fourth ship of the class was canceled and the third ship, *Shinano,* was converted into an aircraft carrier, although it never engaged in active combat.[15]

The U.S. Pacific campaign might have gone quite differently if Japan had commissioned two additional aircraft carriers in October 1941 and two more in June 1942 instead of two giant, operationally useless battleships. Recall that, even after losing four aircraft carriers at Midway in June 1942, Japan still possessed a three-carrier advantage over the United States in the Pacific.[16] Even without our engaging in a detailed counterfactual exercise, given the ferocity of the operations that followed, if Japan's post-Midway margin of superiority in aircraft carriers had been seven instead of three, it is likely that years more of fighting and tens of thousands more war dead would have been required to achieve the probably still-inevitable American victory.

The IJN was neither innocent of nor blind to the new naval technologies that emerged during the interwar era. It embraced many advanced technologies in its warship designs and made innovative use of aircraft carriers, fixed-wing naval aviation, submarines, torpedoes, land-based naval aviation, radio, and amphibious warfare. Neither was its embrace of these technologies a matter of mere theory; their application in Japan's lightning victories in its early Pacific campaigns serves as clear demonstration of effective conceptualization and implementation of interwar naval war-fighting technology.

Japan sought to overcome the disadvantages of its smaller battleship fleet by extending existing warship-design practices to build larger battleships that would leapfrog ahead of the capabilities of the notional American foes they were expected to face. In that sense, *Yamato* embodied the culmination of fifty years of successful Japanese fleet operations and ship-design evolution. The ship's concept of operations was well founded in established Japanese naval doctrine, which proceeded from broadly accepted principles of modern naval warfare, as articulated by Alfred Mahan in the 1880s.[17] These core operational principles were developed in combat during the Sino-Japanese War of 1894 and refined further during combat operations in the 1904–1905 Russo-Japanese War and against Germany during World War I.[18] Japanese warship-design principles followed proven and mature engineering principles, extending them as emerging technology permitted to meet expected operational war-fighting needs effectively.[19] Lastly, Japan's decision to build *Yamato* was consistent with the battleship-centric plans of all other major navies at the time.[20] *Yamato*'s design and operational requirements emphasized lethality and survivability within a well-established analytical warship-design philosophy. Yet not only did those well-founded, analytically pure decisions fail to enable victory at sea, but they contributed to imperial Japan's eventual defeat in 1945.

**Wahoo: *The New Multimission Ship***

USS *Wahoo* was a historically significant submarine of the *Gato* class (often referred to as "fleet submarines"). *Wahoo* and its sisters were designed to provide fleet reconnaissance and distant support for the American battle fleet. That fleet was built around a core of powerful battleships attended closely by cruisers and destroyers. Submarines like *Wahoo* were to be assigned as advance scouts to find, track, and report on the Japanese battle fleet. If possible, the submarines were to conduct attrition attacks of opportunity against Japanese warships, but on a not-to-interfere basis with their primary role of reconnaissance and reporting.[21] To support American fleet operations in the vast Pacific theater, their design and operational doctrine maximized transit speeds and endurance, while remaining in compliance with treaty limitations on individual submarine size and characteristics.[22]

During the interwar period, both the United States and Great Britain considered unrestricted submarine warfare against unarmed merchant ships to be both immoral and illegal. Germany's use of those tactics almost had lost World War I for Britain and had been the principal basis for a deeply isolationist America's entry into that war.[23] Both nations pushed hard, but unsuccessfully, to include restrictive language prohibiting unrestricted submarine warfare against merchant ships into the naval-arms-limitation treaties of the interwar period. It was official U.S. policy that American submariners would not plan or train for, nor conduct, any such attacks.[24]

But, as with *Yamato,* these operational concepts did not turn out as expected in practice. On 8 December 1941, as the core of the American battle fleet lay smoking in the muddy waters of Pearl Harbor, the United States declared unrestricted submarine warfare against Japan. Thus, the fundamental premises of the operational and design principles of American fleet submarines, developed and inculcated over two decades, were invalidated within hours of the commencement of combat operations against Japan.[25] Yet *Wahoo* and the other *Gato*-class submarines went on to sweep the seas of Japanese merchant ships, fighting well above their weight after 1943.

Through sheer happenstance, the ship-design characteristics necessary to execute the fleet-reconnaissance mission in the Pacific Ocean matched almost exactly those needed to execute long-range, unrestricted submarine *guerre de course* against the Japanese empire. A seventy-five-day patrol duration, prodigious torpedo capacity, a modest surface-gunnery capability, nominal self-defense capability against aircraft, rapid dive capability, long submerged duration, high surface speed, and advanced torpedo fire-control systems were necessary attributes for both mission sets, and *Wahoo* and the other *Gato*-class submarines possessed them all. In fact, *Wahoo*'s ten torpedo tubes and twenty-four-torpedo loadout were almost double the five tubes and fourteen-torpedo loadout of a Type VII German U-boat of the same period. *Wahoo*'s unrefueled 11,000-nautical-mile (nm) range was far superior to the Type VII's 8,500-nm range, even though Germany had designed its U-boats specifically to conduct unrestricted submarine warfare against merchant ships.

Despite the more than satisfactory technical characteristics of *Wahoo* and its sister ships, America's implementation of its new policy of unrestricted warfare against Japan was exceptionally slow.[26] Infamously defective torpedoes and less-well-known engine-performance issues with the submarines that preceded the *Gato*-class boats, doctrinal disputes, and the timidity of American submarine captains limited the combat effectiveness of American submarines until well into 1943. During those early years, USS *Wahoo* and its famous captain, Lieutenant Commander Dudley "Mush" Morton, and its even more famous executive officer, Lieutenant Commander Richard "Dick" O'Kane, along with a few other pioneering officers, led the way in finding, defining, and demonstrating the *Gato* class's inherent but latent combat capabilities.[27]

Engines and torpedoes could be fixed and new commanding officers trained and assigned. American submarines in the Pacific eventually waged the most successful unrestricted-submarine-warfare campaign in history—far more effective than that of their German counterparts in the contemporaneous Battle of the Atlantic.[28] The prewar design of American submarines formed the technical foundation of victory from 1943 to 1945, even though the actual operational environment was unexpected and ran counter to the expectations embedded in twenty-five years of explicit American naval war-fighting policy and doctrine.[29] Had the United States been required to design new submarines to perform a completely new, previously undefined mission starting in 1941, the course of the Pacific campaign would have been profoundly and negatively affected. America got lucky.

**Hornet:** ***A Ship of the Future, a Ship for the Ages***

The concept of an aircraft-carrying ship was born and almost fully matured to its modern form by Britain's Royal Navy between 1914 and 1918 with the conversion of the 14,000-ton HMS *Argus* in 1917–18.[30] It had a flight deck stacked on top of an enclosed hangar deck and vertical elevators to move aircraft between them; it was missing only an island and catapults. In the United States, the 12,000-ton

USS *Langley* (CV 1) was converted from a collier in 1922 as a low-rent version of *Argus*. America's much larger follow-on carriers, the 37,000-ton USS *Lexington* (CV 2) and USS *Saratoga* (CV 3), were converted from incomplete battle-cruiser hulls in 1927. Both were considered "too big" at the time, with their size having been dictated by the hulls on which they were built rather than by aviation warfighting requirements.[31] Invoking standard ship-design philosophies to build the first American aircraft carrier designed from the keel up produced the 14,000-ton USS *Ranger* (CV 4) in 1934 and the similar USS *Wasp* (CV 7) in 1940.

But in the four years between *Ranger*'s design and commissioning something happened that brought the entire philosophy behind that design into question. The airplanes it was intended to embark became obsolete and were replaced with much larger, more-powerful aircraft. Although *Ranger* incorporated many successful innovations—most notably, an open hangar bay dedicated to maintenance and ammunition loading, a starboard above-deck island, flight-deck "galleries," and some limited gun armament—USN designers quickly realized that their warship-design paradigm was flawed.[32] Between 1927 and 1940, the U.S. Navy fielded three generations of frontline fighters whose takeoff weight and engine horsepower (hp) increased from the 2,750 lb, 450 hp Boeing P-12/F4B in 1927 to the 7,952 lb, 1,200 hp Grumman F4F Wildcat in 1940. Attack aircraft showed similar generational growth, culminating in 1942 with the 15,905 lb, 1,700 hp Grumman TBF Avenger. Dive-bombers did not exist in 1927 but joined the American air wings in the late 1930s. This sustained pace of weapon-system development was unprecedented in the history of naval-weapons technology; new airplane models were fielded every eighteen to twenty-four months.[33] The American naval-aviation community did not follow long-established naval-warship-design practices, and the U.S. Navy could not afford to build a new ship every time a new airplane was invented.[34] A different design approach was needed.

The solution was to decouple the weapon (aircraft) from the ship as much as possible. Rather than having hundreds or thousands of design touch points—called interfaces—between the weapon and the ship, the Navy's aircraft carrier design team sought to minimize and standardize these interfaces. Greater excess margins for weight and power were added to accommodate unknown future growth in aircraft characteristics. Defining maximum landing weight, takeoff wind, deck loading, elevator lift capacity, hangar dimensions, aviation-fuel load, and bomb-storage capacity allowed ship designers to isolate themselves from the pace of change in the aviation community.[35] A new ship would be required only once one or more of those key interfaces or ship-design margins were going to be violated by the characteristics of a new air wing.

*Ranger*'s design flaws were corrected in the three ships of the 25,000-ton *Yorktown* class, which comprised its namesake, USS *Enterprise* (CV 6), and USS

*Hornet* (CV 8), commissioned in 1937, 1938, and 1940, respectively. The class improved on the "too big" *Lexington*-class hulls and incorporated the hard lessons of the inadequate *Ranger* and *Wasp*—ships that were functionally obsolete before they were commissioned.[36] Like *Saratoga* and *Lexington, Hornet* was a big, roomy ship with large elevators, a fast hull, clearly defined air-wing interfaces, and generous design margins.

After Japan's attack against Pearl Harbor on 7 December 1941, President Franklin Roosevelt directed an attack on Japan's home islands. The Navy tried to demur, because most of the battleships it traditionally would have needed to enable such an attack would require years of repairs before they were ready for an offensive campaign. The Army had no bomber with the necessary range. Roosevelt was undeterred, and within a few weeks a Navy-Army team determined that a new Army medium bomber, the B-25 Mitchell, theoretically could take off from a *Yorktown*-class aircraft carrier deck with enough relative wind over the deck. Several weeks of testing ashore convinced commanders that it could be done, and the Doolittle Tokyo raid was conducted successfully on 18 April 1942 from *Hornet*—just four months after the Pearl Harbor attack.[37] Although militarily insignificant, the attack was a huge psychological success, crushing Japan's self-image of impregnability and boosting American morale at a critically low point.[38] It was brilliant, and brilliantly executed.

Had anyone proposed that Army bombers operate from Navy aircraft carriers before December 1941, they would have been not only laughed at but probably removed from their jobs as well. There was no chance of such a suggestion being written into a ship-requirements document or included in a ship design. No ship designer envisioned it, and no war plan proposed it—but it surely was needed, and it happened.

B-25s happened to fit within enough of *Hornet*'s design interfaces to permit pierside loading and afloat fueling, arming, and takeoff. To use modern terms, the pace of aircraft development forced the aircraft carrier designers to invent an open-architecture design approach, and it decoupled the ship from the embarked air wing. The designers focused primarily on defining clear interfaces to an embarked "mission module"—the air wing—rather than the internal technical or war-fighting details of that mission module—the airplanes. Rather than fully and inclusively defining all the desired missions of a ship, then designing it to meet that exact capability—as with *Yamato*—the new aircraft carrier approach broadly defined a "capability to have a capability" by not overspecifying current capabilities, leaving the operational door open for future, unknown mission-module (i.e., air wing, ordnance, and embarked personnel) war-fighting capabilities.[39] Lethality was removed from the ship-design process, ceding that characteristic to the embarked air wing.

The result has been profound and revolutionary. Aircraft carriers now routinely serve continuously for up to fifty years as operationally relevant, first-line warships. That has not happened for surface combatant ships since a forty-year-old HMS *Victory* fought at Trafalgar in 1805. Aircraft carriers routinely and easily accommodate major advances in war-fighting technology that were unknown at commissioning.[40] USS *Midway* (CV 41) was designed in 1943 with Mitsubishi Zero fighters and Betty bombers in mind, but spent most of its forty-seven-year service life carrying jet fighters operating against supersonic Backfire bombers carrying nuclear cruise missiles, interspersed with combat missions to Korea, Vietnam, and Iraq, among many others. Beyond the Zeros and Bettys, none of this was, or could have been, anticipated by the ship's original designers. And *Midway* was not unique; quite a few other major World War II–era warships saw similar extended frontline service lives—all of them aircraft carriers.

## THREE SHIPS, THREE DESIGN PHILOSOPHIES

*Yamato* represented the culmination of four centuries of successful ship-design practices, incrementally optimizing explicitly defined operational requirements into pristine, tightly constrained designs that met highly detailed war-fighting requirements for lethality and survivability. *Wahoo* and its *Gato*-class sisters accidentally discovered the advantages of being capable of conducting multiple primary war-fighting missions. *Gato*-class submarines had operational characteristics that permitted them to operate effectively in other closely related warfare missions beyond what had been designated originally. After all, sinking a merchant ship at sea is not too much different from sinking a warship; if anything, it may be easier. *Hornet* broke the mold, demonstrating the combat value of a completely new open-architecture, adaptable ship-design approach. Designing for an interface to an embarked weapon rather than to a specific combat mission allowed the U.S. Navy to change the ship's mission easily by changing its mission module—the embarked air wing. In the decade before the Pearl Harbor attack, the number of viable warship-design philosophies tripled. In the subsequent eight decades, there has been a broad failure to appreciate the differences and trade-offs among them, to the detriment of many shipbuilding programs.

### *The Foundations of Modern Ship Design*

So, how did *Yamato*'s flawed design happen? Why was *Wahoo*'s mission so poorly defined? Why did the naval officers and engineers responsible feel so sure in their approach to *Yamato* and most of the other surface combatant ships in their fleets? The answers lay in the origins of modern fighting-ship design in sixteenth-century Europe.

Elizabeth Tudor, daughter of King Henry VIII, ascended the throne of England as queen on 17 November 1558. Elizabeth I's new domain was bankrupt, torn by religious strife, resource poor, and diplomatically isolated. Worse, the leader of the most powerful nation in the Western world, King Phillip II of Spain, believed that he was the rightful king of England as a result of his marriage to Elizabeth's since-deceased half sister, Queen Mary I, who preceded her on the throne. Elizabeth had caught a tough assignment, but she was very much up to the challenge.[41] Recognizing that her first priority was to refill the depleted royal treasury, England's new "Pirate Queen" invoked the "Willie Sutton rule" 350 years before it was first articulated; she dispatched her sea captains to steal Spanish treasure en route to Europe from the New World.[42] Sir Francis Drake, Sir Walter Raleigh, Sir John Hawkins, and their fellow English captains were moderately successful in this effort.

However, they soon reported problems with their ships in battle against their intended Spanish victims. The "warships" of Elizbeth's early reign rarely were purpose-built; instead, most were temporarily converted merchant ships. Superstructures (called "castles") and small guns were added during the short Atlantic fighting season. High castles forward (from which the nautical term *fo'c'sle* derives) and aft enabled plunging fire from handheld weapons against galleys and unmodified merchant ships. Larger, mounted weapons were fired over bulwarks; the idea of cutting holes in the sides of ships for deck guns was an emerging, risky technology first tried in 1501.[43] When not engaged in naval service, these ships would be stripped of their war-fighting gear and operate again in merchant service to offset their annual operating expenses.

These makeshift warships were slow and difficult to maneuver. Clumsy handling characteristics were not a significant problem for hauling cargo but were liabilities in a fight. Spanish ships were armed with guns made for the army that were unaltered for naval service and were operated by embarked soldiers; the sailors sailed and the soldiers fought. The Spanish employed shoot-and-board tactics; they approached directly toward an enemy ship, fired their heavy guns once, and then grappled and boarded the target vessel to overwhelm the enemy crew with crossbows, small arms, and sword- and pike-wielding soldiers. As has been the practice of land powers afloat for centuries, Spain turned sea fights into land fights. The Spanish also adopted the Mediterranean oared-galley practice of mounting a few very heavy guns on their bows that could fire only forward, creating the *galleon:* a ship with the low bows of a galley to accommodate big, forward-firing guns and the high stern of a converted merchant ship to enable plunging fire when alongside an enemy.[44] Ship's guns of the day were a century away from using recoil mechanisms to permit reloading from inside the ship. Instead, guns were reloaded in place by gun crews hanging over the side of the ship on ropes and in bosun's chairs—a time-consuming and difficult task even for experienced sailors, and not one that soldiers did well. Still, the galleon's design suited Spanish fighting tactics while retaining the ships' inherently mercantile mission of hauling treasure from the New World back to Spain.

King Henry VIII, Elizabeth's father, had been a gun and ship enthusiast.[45] He liked the flash and bang of guns—the bigger the better—and he liked the power and pomp of a big ship. Elizabeth inherited a navy with few soldiers and many guns; sailors fought, manned the guns, and sailed the ship. To defeat the heavily crewed Spanish ships and their aggressive frontal attacks, English ships needed to be able to stand off from their targets and fire their guns, trying to kill as many Spanish soldiers as possible to even the odds before closing to board and seize the galleon's cargo of treasure. English ships needed to be faster, more maneuverable, and more heavily armed than their Spanish opponents.

To achieve greater speed and maneuverability, English ships needed to be slimmer and carry more sail; to overwhelm the heavier Spanish ships, they needed to carry as many guns as possible, both broadside-firing and forward-firing. These characteristics were entirely incompatible with the ones that made a good merchant ship of the day; lethality and survivability needed to dominate, while as many other ship characteristics that reduced those qualities as possible needed expunging. Dedicated warship design was born. The new English warships would be designed "from the keel up" to perform a single, clearly articulated combat mission. These ships enabled English naval tactics that no converted warships at the time could replicate. The new warship would sail toward the enemy, then wheel away at range, firing its guns in sequence as they came to bear. When safely out of range again, English sailors would clamber over the side to reload. Then they would repeat the feat, raking their targets again and again. English ships needed continuous, open internal decks to allow for the free flow of orders, ammunition, and sailors among guns as they executed these complex attacks and maneuvers. Elizabeth's warship designs had to be dedicated to and optimized for war at sea; the vessels no longer could be converted merchant ships. The result was the fast English galleon—one of the first true, from-the-keel-up, sailing warship designs.[46]

Standardized ship designs permitted different English shipyards and dockyards to build similarly performing ships, enhancing their combat performance when operating together. Elizabeth was the first English monarch to provide shipbuilders with ship-performance specifications, a prototypical version of "build to print" contracting.[47] She also needed an effective and efficient naval infrastructure to manage and maintain these ships, since they no longer could offset their operating costs by hauling cargo in the off-season. She added capacity to her father's pioneering naval depots and dry docks, supplemented their infrastructure, and built an efficient civil naval administration—the precursor of the British Admiralty.[48] The purpose of all this was to store, manage, care for, and protect the ships and their equipment, stores, and armament when they were not actually fighting—which is to say, most of the time.

Bereft of money but awash in recent combat experience, Elizabeth and her sea captains defined a lean, tightly coupled design-build process. The naval administration they established to manage that process consistently delivered lethal and survivable ships using available technologies that exactly met her immediate operational maritime needs at minimum cost and with maximum operational effectiveness.

The result was brilliantly effective, as demonstrated during the many failed Spanish armadas of the late sixteenth century. The most famous was the doomed armada of 1588, made up of ponderous, overmanned, poorly led, poor-sailing, and overloaded ships; Elizabeth's purpose-built warships sailed circles around them. Ammunition usage data from the fighting show that the Spanish ships fired, on average, one shot per gun per day, while English ships fired each gun one to one and a half times per hour.[49] As a result of this extraordinary firing-rate disparity, the Spanish Armada never ran out of ammunition before its ultimate destruction, while the English fleet ran out several times. In fact, obtaining more ammunition for unexpectedly depleted shipboard magazines quickly defined and constrained English fighting operations after the first day of the weeklong battle.

The fleet- and ship-design approach that produced the successes of Elizabeth's Navy Royal matured over the ensuing centuries into the modern warship requirements definition and design process.[50] The iterative process began with a clear definition of the immediate operational environment, explicitly defining the new weapons (lethality) and innovative ship characteristics (survivability) that meeting the defined mission required; then it optimized the warship's design to remove all other nominally unnecessary characteristics. The process was repeated for the next generation of warships, then refined, repeated, and refined again ad nauseam until it produced the modern steel warships that appeared in the early twentieth century.

That iterative process repeated until 21 May 1934, when the keel of USS *Yorktown* (CV 5), lead ship of the class that included *Hornet,* was laid at Newport News Shipbuilding and Drydock Company in Newport News, Virginia. *Yorktown* was the result of an entirely new approach to naval technology and warship design. As with Queen Elizabeth I's Navy Royal, this methodological revolution was a response to new technologies and new war-fighting requirements that existing design processes were inadequate to address. Nearly four hundred years of established naval-ship-design practice should have come to an end at that point; regrettably, they did not.

***Surface-Ship-Design Practices***

Elizabethan design methods were effective as long as naval technology evolved at a pace roughly in step with contemporaneous ship life cycles of forty to fifty years. The method began to unravel when the rate of technical innovation in naval technology started to accelerate during the Industrial Revolution. Steam propulsion technology first moved afloat in the early 1800s and was becoming mainstream by the 1830s.[51] Gun, gun-propellant, and ship-armor technological advances followed quickly through the Crimean War, the American Civil War, and the emergence of the modern steel navies in the 1890s, culminating with the all-big-gun battleships of World War I fame.[52] The long century between the Battles of Trafalgar (1805) and Jutland (1916) was the most innovative in the history of naval technology to that point. A British sailor transported from Sir Francis Drake's flagship *Revenge* in 1588 would not have been uncomfortable aboard HMS *Victory* at Trafalgar, both sailing warships; a sailor from *Victory* would have been completely lost on board Admiral John Jellicoe's flagship at Jutland, the dreadnought HMS *Iron Duke*.[53] The technological differences between *Victory* in 1805 and the first all-big-gun battleship, HMS *Dreadnought* in 1906, comprise, in my opinion, the greatest degree of change across any one-hundred-year period in naval history. But it did not stop there. By the time of the Battle of Jutland in 1916, *Dreadnought* itself—archetype of the modern battleship—was deemed so obsolete that it was left out of Britain's Grand Fleet, just ten years after it was commissioned. *Dreadnought* was scrapped in 1919, while barely a teenager.

Throughout this century of radical technology innovation, Elizabethan-school design principles nevertheless held strong despite the limitations that clearly were emerging. New weapons, new propulsion technology, new armor, and new operational requirements all necessitated substantial ship-design changes to implement. Most warships could not be retrofitted to accommodate new technologies. Under the Elizabethan-school design rubric, major maritime innovation required building new ships. To compensate, design-build cycles were shortened; new ship classes were designed almost annually, with each year's more lethal and survivable designs improving on, and even eclipsing, the previous ones. The pace of advancement became so fast that ships often became obsolete before they were launched.[54] New ships had to be built whenever a major new war-fighting technology was developed. Elizabethan-school design principles, focused only on meeting contemporary lethality and survivability requirements, removed future adaptability and flexibility from baseline class designs. Margins for growth and adaptation were, and often still are, seen as waste.[55] Ships were built to meet the day's threat with the day's technology, and tomorrow's war-fighting needs were judged to be a problem for tomorrow's leaders. As a result, planned ship-service lives were achieved rarely, if ever. Modernization, if attempted, was invariably a long, expensive, and often unsatisfactory process.[56]

A technical note on design margins and interfaces. *Margins* are excess capacities in key characteristics such as displacement, power, cooling, and stability that are designed into ships above what the current systems on that ship require to allow for future modernization and additional equipment. Margins allow for real growth in those characteristics up to their defined (and design) maxima. *Interfaces* are the connections between systems within a ship. Interfaces allow for changes on either side of the interface without breaking functionality on the other, so long as both sides comply with the interface standard. Interface standards are why, without affecting the power company's grid, you can plug your new lava lamp into the same electrical outlet into which your clock radio used to be plugged. Likewise, your lava lamp will continue to work when the power company switches from coal- to solar-power generation. Margins are why you blow a fuse or trip a breaker if the appliances you plug in draw too much power.

After World War I, maritime technology continued to change rapidly. In a 1936 paper, Britain's director of naval construction observed that between 1920 and 1935 the weight of antiaircraft armament on warships tripled, deck protection weight quintupled, and the weather-deck area occupied by aircraft and their associated equipment went from 0 to 20 percent. And "all of these increases had to be accommodated in a hull limited in size by the [naval arms] treaties."[57] No consideration was given to unexpected operational requirements. In fact, had those treaty restrictions been relaxed, "there is every reason to believe that the major navies would have simply opted for more main guns and more torpedoes."[58] This is exactly what happened when *Yamato* was designed, once freed from those treaty restrictions. The Elizabethan-school design philosophy's ruthless optimization imperative did not allow for any other path.

By contrast, American aircraft carrier commanders in the Pacific theater discovered, in the early months of the war, the crucial operational flexibility that open-architecture ship design provided. After the Battle of the Coral Sea, in May 1942, American commanders complained that their strike-heavy air wings needed more fighters instead. Within *three weeks* the fighter allocation to air wings was increased by 69 percent—just in time to make a material contribution to the U.S. victory at the decisive Battle of Midway, in June 1942.[59] Similarly, American dive-bombers, as noted earlier, were unknown when the first American aircraft carriers were designed in the 1920s and early 1930s. But they proved to be decisive in those early Pacific naval battles—just five years after they were introduced afloat.[60] For comparison, no battleships or cruisers ever doubled their air-defense capability in three weeks or changed out their principal weapon system in less than five years.

After World War II, American warship design bifurcated, with a new *Hornet*-style process applied to aircraft carriers and an updated Elizabethan-school process applied to new, multimission surface combatants. Maritime operations in World War II finally had exposed the fatal limitations of the classic single-mission

Elizabethan-school approach while illuminating the new, derivative, multimission path discovered in *Wahoo* and other ship classes during the war. Battleships, largely unable to perform their primary surface-warfare mission for want of targets, became artillery platforms for shore bombardment in support of amphibious assaults and air-defense platforms for task groups and fleets. Destroyers became radar pickets, antisubmarine platforms, and air-defense ships, in addition to performing occasionally their prewar designated mission as surface escorts.

The U.S. Marine Corps proved to be as disruptive to American ship designers as the naval-aviation community had been, and amphibious ship designers quickly adopted the same open architecture and flexible ship-design approach used for aircraft carriers. This left the Marines free to buy new tanks and amphibious assault vehicles without having to make the U.S. Navy buy new ships, so long as they complied with defined interface and margin standards.[61]

In brief, aircraft carriers and amphibious ships demonstrated the design implications of "cross-domain" ships. Aircraft development and the Marines did not follow Elizabethan-school ship-design rules, instead changing and modernizing at a far faster pace than the ship-design and shipbuilding communities could tolerate. The solution, logically enough, was to separate, in a controlled way, those noncompliant domains (aviation and amphibious operations) from the ship domain in the ship design; interfaces and margins had to become the connection (and insulator) between the slow-moving world of ship design and shipbuilding and the high-speed worlds of amphibious operations and naval aviation. By way of analogy, interfaces and margins are like the gearing that allows a high-speed automobile engine to be coupled to a low-speed tire or a high-speed marine gas turbine to be connected to a low-speed ship propeller. Aircraft carriers and amphibious ship designs are thus "loosely coupled" to their *embarked* weapon systems through a defined set of interface standards and design margins.

Surface combatants, however, were not subject to the same operational discontinuities and frequent disruptions of the aviation and amphibious communities, leaving their designers comparatively free to follow the old rules—slightly modified by adding *Wahoo*-like multimission capabilities—in peacetime. Surface-combatant designs did not have "gearing"; they were "direct drive"—new weapon systems required new ships. Surface combatants retained the traditional, Elizabethan-school "tight coupling" between the ship and their *installed* weapon system. *Embarking* versus *installing* weapon systems became the principal design differentiator between *Hornet*-like ships and *Yamato*- or *Wahoo*-like ships.[62]

But advances in surface-ship technology since the 1950s have seen the same high rate of obsolescence as before World War II, if not greater, challenging the modified Elizabethan-school approach. Missile, radar, and computer technologies all saw rapid innovation, generating a series of war-fighting capability leaps.

The new multimission approach (i.e., *Wahoo*-like) appeared to offer an easy solution to the problems this pace of innovation posed. It allowed fewer multimission ships to replace larger numbers of single-mission ships (and, later, multimission ships capable of fewer missions) while still introducing new technologies exclusively through the ship-design and shipbuilding process, exactly as had been done for centuries; as a result, fleet size collapsed but fleet combat capability multiplied. This technology environment perpetuated the same high rate of design turnover and abbreviated warship service lives that had plagued advanced navies since the 1830s; deploying significant new surface-combatant war-fighting technologies still required building new ships.

Facing their own new, internal, accelerating technology drivers and constrained by the Elizabethan-school ship-design process, shipboard weapon and system developers (e.g., of radar, sonar, and fire-control systems) began to adopt the approaches developed by aircraft carrier designers in the 1930s and amphibious ship designers in the 1950s. They established strict interface standards and clearly defined margins within the confines of the systems they developed for surface combatants. Formal engineering principles of modularity, adaptability, and flexibility began to be developed in the 1960s in response to this high rate of technological change, and they have produced enduring capabilities that long outlasted the first hulls into which they were installed.[63] The computer-controlled, software-based SPY-1 radar, in all its versions and descendants, in combination with standardized computer designs and software methods, allows war-fighting-capability improvements to be implemented through computer software upgrades far more easily and cheaply than modernizations that require a hardware redesign and installation. Modular vertical launching systems (e.g., VLS) permit new missiles to be deployed without having to install new launchers unique to each missile. Despite these system successes, surface combatant ship designs remained products of the time-tested Elizabethan-school processes and methods; once weapon-system hardware (radars, launchers, computers, etc.) were installed, major changes and hardware modernization of weapon systems became difficult, if not impossible.

Warships today are collections of independently developed systems, each with its own development plan, budget track, and sustainment plan. The genius behind the Aegis system was to integrate the entire air-defense detect-to-engage sequence into a single, unified system with common development, execution, and sustainment processes.[64] But despite Aegis's four-decade record of success, this level of integration is only beginning to emerge in other types of systems installed in modern, multimission warships.

As with *Wahoo*—whose secondary mission, attrition attacks against enemy warships, became its primary mission at the start of World War II, just applied to merchant ships—modern multimission ships can accommodate new threats so long as the threat emerges within the explicitly defined capabilities of the ship's existing weapons; any new threat that emerges within the limits of that extant "mission space" can be addressed with few or no modifications to the ship's systems. The addition of a ballistic-missile-defense (BMD) capability to selected Aegis-equipped warships after the Cold War demonstrates this sort of mission flexibility. Sometimes even these expanded capabilities themselves can be expanded for new missions, as in 2008 when USS *Lake Erie* (CG 70) successfully conducted an antisatellite mission using a space-intercept capability inherent in its existing BMD capability, which itself was a modification of the ship's existing Aegis area-air-defense capability.[65]

Being unable to add unexpected war-fighting capability doomed volume production of the new *Zumwalt* class of ships years before the first ship was commissioned.[66] The first five ships of the *Ticonderoga* (CG 47) class were decommissioned after as little as eighteen years of service because they could not accommodate new missiles and new hardware, just as HMS *Dreadnought* had been scrapped eighty-six years earlier for similar reasons. The technology was new but hampered by the same old ship-design process. From my time as a junior naval officer, I remember a Terrier and Tartar missile "New Threat upgrade" being installed on dozens of ships decades after a Soviet "New Threat" antiship missile was fielded, then those recently and expensively upgraded ships were decommissioned just as quickly and en masse after the Cold War ended. The price of inflexibility created by focusing ship designs principally on contemporary threats continues to be high.[67]

Today, it is even more difficult to predict what is required from encounter to encounter, much less from year to year, and, as well articulated in 2011 by former Secretary of the Navy Richard Danzig, it is almost impossible to predict war-fighting requirements any more than a decade into the future.[68] Paradoxically, weapons technology is changing even faster today than it did during the Cold War.[69] More importantly, it is changing in unpredicted and unpredictable ways. Aggressive international sales of sophisticated weapon systems quickly proliferate tough new threats globally.[70] In addition, modern computer technology is no longer dominated by military requirements, as it was in the 1960s and 1970s; the commercial market is driving even more unplanned change into an already challenged weapon-system and ship-design environment.[71]

In brief, the situation facing surface-combatant designers today is the same as that faced by mid-twentieth-century aircraft carrier and amphibious ship designers. Substantial technology issues outside the control of surface-combatant ship designers are creating design dilemmas that materially affect both current and future war-fighting performance. In the 1930s and 1950s, respectively, cross-domain technology requirements overrode existing aircraft carrier and amphibious

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ship design processes. Today, core surface-combatant war-fighting demands are less certain and less predictable, but current installed ship weapon systems have limited capacity to be expanded beyond the explicitly defined war-fighting requirements to which they were built.

Surface combatants now have an equivalent "cross-domain" design driver: *technology.* To generalize a bit, all warship designs are driven by the expected technology requirements of some defined time horizon. When they are built to face an immediate and existential threat, as Queen Elizabeth I's fast galleons were, longer-range technology drivers can be ignored. In this special case, ships are designed and built "today" with today's technology and today's threats in mind, and out of a deliberate choice to "worry about tomorrow, tomorrow." When technology moves slowly, perhaps at the pace of a ship's operational life (nominally thirty to forty years), as it did between 1588 and the early nineteenth century, new technologies can be implemented in new-construction ships in the normal course of business. As the pace of technology change quickens, however, that design rubric becomes less and less palatable, as navies get caught between the high cost of building new ships and the high cost of modernizing existing, old-technology ships.

Separating the ugly details of implementing rapidly changing new war-fighting technologies (such as airplanes, tanks, radars, missiles, and computers) from the long-service, stable technology base of the ship's platform design (hull, engines, electrical power, passive survivability, etc.) as much as possible is a proven way of resolving this conundrum (e.g., *Hornet*). *Lethality*—to use a term in vogue—is a measure of the missile being launched, not the ship launching it. Explicitly separating them by using a clearly defined, stable engineering interface ensures that a navy can achieve rapid technology insertion, affordable modernization, sustainable sustainment costs, and full ship-service-life performance.

This argues for the U.S. Navy to abandon all vestiges of the Elizabethan-school ship-design processes for new surface combatants and adopt a *Hornet*-like modular and flexible whole-ship design process that better accommodates today's dynamic, technology-driven war-fighting environment. I choose to call the *Hornet*-style modular and flexible ship-design process "*Enterprise* design." *Enterprise* design begins in earnest where the ship-design process ends for the Elizabethan school. Modern war-fighting requirements and surface-combatant designs must extend in time beyond contemporary, known needs, and they should seek to support the entire planned service life of the proposed ship.[72] Unbeknownst to them, the engineers who designed USS *Midway* (CV 41) in 1943 were designing a ship that would operate supersonic jet fighters in 1983; they had no idea that was what they were doing, or even that naval jet fighters might soon exist outside 1940s science-fiction stories.

This is different from improving or enlarging design margins. *Midway* had design margin when it was built, and new margin was added throughout its service life to accommodate new flight-deck structures, elevators, steam catapults, and arresting gear. The capacities of those devices, in terms of size, weight, point loading, and so on, are the interface points between the ship and the aircraft, not margin. Those interfaces can be changed, and they were in *Midway*, but once in place they did not need modification to accommodate new airplanes unless the new airplane exceeded the interface standard. That is why USS *Gerald R. Ford* (CVN 78) needed new and different catapults and arresting gear from those of the *Nimitz* class it is replacing; the expectation is that the airplanes of the future (especially uncrewed aerial vehicles) are going to break the interface standards of the Navy's existing 1950s-era shipboard-aviation systems.[73]

Since it is, in practice, impossible to know in detail what war fighting will require twenty to thirty years into the future, critical surface-combatant design parameters must focus more on the capability to accept future change than on delivering a ship that meets today's defined war-fighting capabilities. A new ship not only must have sufficient war-fighting capability at commissioning; it also must have an extended "capability to have a capability" throughout its planned service life. A ship must be commissioned with a "minimum viable capability" (e.g., F4U Corsairs on *Midway* in 1946) but with interfaces and margins that can accommodate a radically different but operationally necessary capability late in its service life (e.g., F-18 Hornets on *Midway* in 1990).[74]

The U.S. Navy's thirty-eight (as of fall 2021) operational littoral combat ships, expeditionary transfer dock, expeditionary mobile base, and expeditionary fast transport vessels are modular, flexible ship platforms that already embody some version of the *Enterprise* ship-design process, absent an explicit life-of-ship war-fighting requirement. They are the pioneers of this sea change for the American surface navy. These ships, together with the service's eleven aircraft carriers and forty-three amphibious ships, mean that the U.S. Navy already has the world's largest national fleet of modular, flexible, adaptable ships. To expand on the potential hinted at by that fleet, the Navy must develop the life-of-ship war-fighting requirements for future surface combatants and determine how to define those requirements to meet unknown future threats, enemies, and operational situations successfully.

### *Return of the Viking Longships*

Viking longships revolutionized ship design and shipbuilding in northern Europe in the late Middle Ages. Their unique "clinker-built" iron-nail and clipped-frame construction made them strong enough to weather the stormy seas of northern Europe but also light and flexible enough to sail up rivers, and even to

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be carried across short land portages. Danish, Swedish, and Norwegian Viking kings sailed their longships throughout Ireland, France, Russia, and England and even into the Mediterranean Sea. Initially these expeditions were exercises in pillaging, killing, and looting but later were used to conquer, trade, and colonize throughout the European continent; the Vikings' flexible, adaptable longships could carry colonists and goods as easily as warriors.[75]

The modern Royal Danish Navy, descendant of those Viking mariners, has embraced its own version of the *Enterprise* design philosophy to great effect. The Danish navy's combat mission during the Cold War could be defined cynically as being ready to die bravely, valiantly, and quickly in a presumed-to-fail effort to prevent a Soviet naval breakout from the Baltic Sea. This produced a Danish fleet composed largely of conventional torpedo boats, coastal gunboats, and mine-warfare ships.

With the end of that Cold War mission, Denmark's small fleet became largely obsolete, and the Danish navy began seeking new missions and innovative paths to meet them.[76] Rather than developing an immediate, analytically derived conventional maritime mission, as Elizabethan-school design principles would prescribe, the Danes focused on building an inherently flexible "capability to have a capability," to be realized when, and as, new war-fighting requirements and new maritime technologies emerged in the future.[77]

Recognizing that weapon-system obsolescence was the key driver for ship obsolescence, the Danes developed a new technology interface approach called Standard Flex, alternatively known as StanFlex or STANFLEX. StanFlex is a tightly defined, modular-mission payload system for embarking a ship's weapon, mission, and communications equipment. Using standard-size containers with defined interfaces that can be *embarked* in a short amount of time allows a surface combatant to add capability, switch among missions, or modernize installed weapon systems quickly and as needed to support a short-term mission requirement or implement a key technology upgrade.[78] This surface-combatant innovation is exactly like *embarking* new dive-bombers with aircraft carrier air wings in 1937 or *embarking* new Abrams tanks with Marine expeditionary units on amphibious ships without having to build new ships to *install* them.

The success of the modular-payload system led the Danish navy to design all-new warships with StanFlex slots and to install slots on older vessels during major refits. The U.S. Navy may have the largest fleet of *Enterprise*-design ships, but the Danish navy's main battle force now is composed solely of StanFlex-configured *Enterprise*-school ships, establishing it as the most transformed, modular, flexible, and adaptable surface fleet in the world.[79]

Denmark, in turn, has used these modular, flexible ships to build a position of worldwide naval visibility and operational excellence.[80] Danish StanFlex ships have deployed to the Indian Ocean for counterpiracy patrols; to the Persian Gulf, where they provide valuable escort and other war-fighting services; and to the eastern Mediterranean to support the destruction of Syrian chemical weapons in 2012.[81] In each case, the *Enterprise* design of the ships paired with the StanFlex interface system allowed the Danish navy to custom-configure each ship to the special and unique circumstances of each deployment, making them not just multimission but custom-mission surface combatants—exactly like *Hornet.* Today, the Danes are seeking to expand their ships' missions further, well beyond anything their original designers imagined.[82] These are the Danes' new Viking longships—long in tenure and utility. The Royal Navy has made the same conceptual choice for its five new Type 31 frigates—a derivative design of Denmark's StanFlex frigates—with the first scheduled to launch in 2023 and enter service by 2028.[83] Denmark has built a navy for the ages: flexible, adaptable, and perpetually useful.

The key to much of this, as with *Hornet,* is the ability of Danish surface-combatant platforms to support the innovative capacity inherent in StanFlex systems. As was the case with *Hornet,* the ships' capacity for change, implemented through their universal standard interfaces for embarked (versus installed) weapon systems, forms the foundation for a lifetime of operational relevance. Elizabethan-school design philosophy prizes eliminating margins—considering them to be waste—and lifetime margins for weight, power, flotation, and the like between 5 and 25 percent are common in ships designed this way. Denmark's StanFlex ships have design margins between 50 and 300 percent, which, in combination with their StanFlex interface system, makes them highly accommodative to major weapon-systems changes, refits, and technology upgrades.[84] They use a modern shipboard data center (a "private cloud") architecture for hosting software—something the U.S. Defense Department is still modeling, with its emerging "software defined, hardware enabled" system-design rubric.[85] Weapons and control consoles are devices and peripherals to the integrated combat system.[86] Upgrades and customizations mostly involve changing software and possibly changing a StanFlex module. Upgrading a major combat system on a Danish StanFlex ship can be completed in several weeks, whereas an American, Elizabethan-style refit can take months, if not years.[87]

### *LCS: A Model for America's New Surface Navy*

The Littoral Combat Ship class (LCS) is the U.S. Navy's first attempt to implement *Enterprise* design principles in a surface combatant. The LCS class is unique in that it has two variants, a monohull and a trimaran design, that are so different that they are functionally separate classes, despite their common designation. They are small, high-speed, low-draft warships with a minimal crew and modular mission capability. Being such a radical departure from prior U.S. surface-combatant-design experience, the class has had significant issues.[88] Danish designers took twenty-five years to achieve what the U.S. Navy has attempted to accomplish with the LCS in a decade. In addition to the modularity and adaptability requirements, the Navy added challenging high-speed and reduced-crewing requirements to the class, all with minimized weight margins.[89] The LCS challenges many, if not all, of the U.S. surface navy's deeply entrenched Elizabethan-school design principles, as well as operations and war-fighting paradigms derived from that same philosophy.[90] New surface combatants are expected to field as front-line, best-of-class surface combatants whose relative margin of superiority over potential adversary platforms slowly degrades over time. But in practice, traditional ships do not obsolesce gradually; they do so as soon as the next gun or missile is invented and deployed. In contrast, an *Enterprise* ship such as the LCS is deployed with a minimum viable capability and then grows and matures its combat capability as new systems and new weapons are developed; as noted earlier, *Midway* was commissioned operating F4U Corsairs and was decommissioned forty-seven years later operating F-18 Hornets. The LCS is designed to accommodate a comparable corresponding range of future capabilities.

Until the LCS, the U.S. Navy had not fielded a surface combatant without 100 percent of its war-fighting capability fully implemented on the lead ship of the class since USS *Spruance* (DD 963) was commissioned in 1975. Unlike *Spruance,* which used space, weight, and power (SWAP) growth and capability margins to support future growth, LCS modules are designed to be added, removed, changed, or upgraded easily within existing margins and interfaces to provide the ship's combat power. Like *Hornet* and *Midway,* LCS-class ships are expected to evolve their capability over time, rapidly responding to emerging threats, emerging missions, and new technologies. For example, when the U.S. Army canceled its Non–Line of Sight missile program, which the Navy intended to use as the LCS's primary antisurface missile, the Navy was able to replace it with another missile system quickly.[91] For nearly any other surface ship, the loss of its primary missile system would have doomed the entire ship class immediately or necessitated a major refit and modernization effort. As noted before, lethality is determined by the missile being launched, not the ship launching it.

Like *Langley, Lexington, Saratoga,* and *Ranger—Hornet*'s innovative progenitors—the LCS got a lot right, but not everything. In building and operating these ships, the U.S. Navy has learned much and was poised to move forward with better, bigger, and more-advanced *Enterprise*-design surface-combatant ships, incorporating constructive and progressive lessons learned from the original LCS class. However, at present the U.S. Navy does not appear to be applying that experience.

The U.S. Navy's future frigate (FFG[X]) and follow-on to the LCS, the *Constellation* (FFG 62) class, is a regressive multimission ship design. It was developed with iterative Elizabethan-school design methods that focus on immediate lethality and survivability using only current technology and building in only minimal capacity for incorporating future technologies. Its largely off-the-shelf installed systems will deliver defined war-fighting capability from day one for each hull, but at the cost of eliminating all modularity and most features that would permit future adaptability. The design also halves the Navy's already-restrictive warship displacement-growth margins to 5 percent (about 370 tons for each ship in the class, as derived from the published displacement).[92] A nominal additional SWAP margin was added for an electronic-warfare system.[93] This design permits no adaptability and no modularity, and only some of the installed weapon systems have any capability to accommodate unplanned growth. This is despite a broad consensus that future surface-combatant weapon systems will include lasers, rail guns, and a multitude of uncrewed vehicles, which will create additional electrical load and require new launch-and-recovery facilities and storage and repair capabilities (see the table).

It is unlikely that any such future capability-growth requirements will fit into a 370-ton margin or the additional defined SWAP margin, assuming that any of it is still available after the first ship is built, tested, and fielded. As the head of British ship construction noted in 1936, technology-driven war-fighting requirements are likely to change in rapid and unexpected ways, even while the first ship is being built.

One exception to the *Constellation* class's rigid design is its use of the Navy's new SPY-6 air-defense system. This is a fully modular and adaptable system that proceeds from the best outcomes from forty years of experience with phased-array radar technology and the integrated Aegis air-defense system. Over those four decades, the U.S. Navy fielded five major versions of Aegis hardware (SPY-1A; the B, D, and D[V] variants; and SPY-6), along with a dozen incremental intermediate hardware upgrades—about one major modernization every eight years. Conceivably then, over the forty years of the FFG-62 class's expected service life (ten years to build the class, plus the thirty-year service life of the last ship of the class), the Navy should expect to field another five major hardware versions

**EFFECT OF TECHNOLOGICAL CHANGE ON SHIP REQUIREMENTS**

| | Power | Cooling | Personnel | Space | Bandwidth |
|---|---|---|---|---|---|
| Unmanned systems | Little change | No change | Increase | Unclear | Increase |
| Electromagnetic weapons | Increase | Increase | Little change | Increase | No change |
| Long-range targeting | Increase | Increase | Little change | Increase | No change |
| Increasing networking | Increase | Increase | More technical | Unclear | Increase |

*Source:* John F. Schank et al., *Designing Adaptable Ships: Modularity and Flexibility in Future Ship Designs* (Santa Monica, CA: RAND, 2016).

or upgrades to the Aegis system. SPY-6's innovative new design likely will accommodate most if not all future incremental hardware changes, but not the fielding of a potential SPY-10 or SPY-12.

The history of the *Constellation*-class design illuminates the problem that the Elizabethan school's design rigidity poses for accommodating unknown future war-fighting environments and requirements. The contracted FFG-62-class design is derived from a French-Italian design dating from 2007 that is currently in service in France, Italy, Egypt, and Morocco. In my assessment, it is a perfectly adequate design for those navies. The derivative USN FFG(X) war-fighting requirements themselves were developed between 2016 and 2017 to support a planned delivery of the first ship in 2028.[94] Thus, by the time the twenty-ship class is completed in the 2030s, it will be a thirty-two-year-old design filling a twenty-two-year-old war-fighting requirement, with little capacity to accept 2040s capabilities or be modernized to address contemporary war-fighting requirements.

Modern experience shows the sort of modernization challenges a twenty-two-year-old war-fighting requirement embedded in an inflexible ship design can raise. Twenty-two years ago, in 1999, the U.S. surface navy's most pressing material issue was replacing the never-upgraded SPY-1B-equipped *Ticonderoga*-class cruisers and modernizing the first twenty-one ships of the SPY-1D-equipped *Arleigh Burke*–class destroyers built before 1999—without bankrupting the Navy.[95] Going back another twenty-two years to 1977, the previously discussed and costly New Threat upgrade and the original SPY-1A-equipped Aegis cruisers were under construction or in design, and all were decommissioned or decommissioning by 1999. Twenty-two years before those upgrades and designs, in 1955, virtually all the surface combatants then in service would be decommissioned before 1977, save for a few gun cruisers that underwent a costly missile modernization. Given this history and the current pace of change in maritime technology, it appears unlikely that the ships of the *Constellation* class will have much relevant war-fighting capability over much of their planned service life.

That abbreviated combat utility compares poorly with the enduring capability in the *Nimitz*-class and *Gerald R. Ford*–class aircraft carriers and the Navy's amphibious ships. Today, forty-year-old ships carry the latest aircraft (F-18E/F Block III, F-35B/C, and E-2D) as soon as the aircraft are available to their embarked air wings and Marine aviation elements, with no need to change the ship's war-fighting requirements. In 2021, an F-35C squadron embarked in USS *Carl Vinson* (CVN 70), a thirty-nine-year-old ship, for the model's maiden operational shipboard deployment.[96] F-35B aircraft deployed for the first time in 2018 aboard USS *Essex* (LHD 2), which, like *Carl Vinson,* is one of the oldest ships of its class.[97] These deployments proceeded successfully despite, and *Carl Vinson* and *Essex* were unaffected operationally by, delays in fielding the F-35; since the ship designs are decoupled from aircraft-development schedules, they continue to fly existing aircraft as long as needed *without operational impact* until the new designs are ready to deploy.

As a thought experiment, consider what the U.S. Navy's position could have been today had the twenty-one *Arleigh Burke*–class destroyers and twenty-seven *Ticonderoga*-class cruisers that required modernization at the turn of the millennium been built originally as modular, *Enterprise*-designed ships. Those forty-eight ships could be receiving SPY-6 radars today—replacing their original SPY-1A, B, and D systems—the accompanying combat systems baseline upgrades, and modern weapon suites during planned three-month, predeployment, pierside modernization periods. Adding in the two Flight III DDG-51-class ships presently under construction with SPY-6 suites, the U.S. Navy could have had fifty of the most modern, capable, and sophisticated surface-combatant ships in operational service before 2025, instead of just the two Flight III SPY-6 ships currently under construction. Under current plans, and including the twenty planned, less-capable *Constellation*-class ships, the Navy will field only forty-two SPY-6-equipped surface-combatant ships, spread over the next quarter century.[98]

The Navy can do nothing about the design of those fifty destroyers and cruisers today, but the surface-combatant design decisions Navy leaders are making today will bequeath those same modernization and shipbuilding problems to their successors in coming decades. Without modularity and *Enterprise*-design attributes, new surface combatants will need to be built to accommodate some future SPY radar or Standard Missile, let alone some entirely new system such as a swarm of drone weapons, a torpedo-firing underwater uncrewed vehicle, a 6G network, or a zettabyte shipboard quantum data center. Elizabethan-school designs do not survive well in a fast-paced, changing technology environment, whereas *Enterprise* designs thrive. *Enterprise* design, as implemented already in the Navy's aircraft carriers, amphibious ships, and LCSs, and at the weapon-system level within the Aegis program and a few other installed systems, dramatically accelerates war-fighting innovation and technology upgrades over classic Elizabethan-school methods.[99]

The LCS and Aegis demonstrate that the U.S. surface-navy community is capable of true innovation, in the modern way. However, that community has stepped away from learning from or capitalizing on this valuable, hard-won, hard-earned experience—innovation, interrupted.

## THE ROAD LESS TRAVELED

The engineers who designed *Hornet* and its sister ships, while contending with the unexpected implications of these new cross-domain vessels, were making it up as they went along—and they did well. Today, the U.S. Navy has a strong body of

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shipbuilding and -design experience, lessons, and rigorous research and analysis that transcends the innocence of those first aircraft carrier design engineers, creating a capability to make designs that can accommodate unknown future advances.[100] As a prominent economics writer cautions, "It would be reassuring to think of new technology as something we *can* plan. And sometimes, it's true, . . . [b]ut these examples are memorable in part because they are unusual. . . . [T]he idea that we can actually predict which technologies will flourish flies in the face of all the evidence. The truth is far messier and more difficult to manage."[101]

To escape the costs of either modernizing or replacing rigid warship designs, the Navy must abandon its Elizabethan-school engineering comfort zone for future surface-combatant designs and instead embrace the engineering sea change begun in 1934 by modularizing both ships *and* shipboard weapon systems. Formally separating the details of specific war-fighting capabilities (lethality) from the ship design and focusing instead on defining a robust but minimal set of ship-to-weapon engineering interfaces, with appropriate (i.e., generous) margins, is a proven method for enabling future flexibility and adaptability; the Navy has been doing just this for nearly eighty years with its aircraft carrier designs. Warships cannot be "future proofed," but they can be designed with the inherent resilience and capability for growth necessary to enable future generations to respond effectively to the still-emerging challenges of the twenty-first century using the ships the Navy is building today.[102]

*Hornet*'s designers were unconcerned about B-25 takeoff weight or ordnance load, because B-25s did not exist when *Hornet* was being designed in 1934; the first B-25 flew in August 1940, just four months before *Hornet* was commissioned. But the Army bombers were able to take off from its decks on a radical, "game changing" combat mission just twenty months after the first B-25 flight. That did not happen because the Navy planned for it; it happened because *Hornet*'s design did not preclude it from happening.[103] *Hornet* was designed and built with a "capability to have a capability"—innovation, unbound.

## FIGHTING TODAY FOR THE FUTURE

The U.S. Navy has a long history of coming up with the right "stuff" at the right time, so that, when wars started, it had the right ships, airplanes, and systems to accomplish its early war-fighting tasks. Despite the interwar financial strain during the 1920s and 1930s, when naval disarmament treaties and then the Great Depression decimated both the service's budgets and the composition of its fleet, the Navy designed largely the "right" fleet for fighting the war in the Pacific.[104] *Wahoo* and *Hornet* were both designed and built during those lean and tumultuous decades. All the hard design and conceptual work was done before the first shots of America's part in World War II were fired, so that all American industry needed to do was push its war-production capacity "full speed ahead" without having to wait to design new ships.[105]

Today the Navy is at a critical juncture; it faces many choices ahead to ensure it can deploy a strong, diverse, innovative toolbox of technologies against emerging and future threats. But like *Yamato*'s designers and builders, who looked solely to the past to predict the future, the U.S. surface navy also is burdened with unhelpful design history. Yet with *Hornet* and its sisters, the Navy looked forward, not backward, to design and build ships that proved themselves victorious in a deadly new combat environment against a formidable foe. The naval-aviation community has perpetuated that success now for decades in the face of dozens of new technologies and completely unexpected maritime operational environments.

Against growing, or at least uncertain, future threats, the Navy's surface community cannot deploy the latest capabilities in sufficient quantity using traditional, Elizabethan-school approaches to design. To attain the advantages of flexible, adaptable operational capabilities that the naval-aviation community has enjoyed and nurtured for nearly a century, it likely has to make hard choices to sacrifice some near-term performance and war-fighting requirements to ensure its ships retain long-term relevance. But as legendary race car driver Mario Andretti is often quoted as saying, "If everything seems under control, you're just not going fast enough."[106] Now is the time for the Navy to "go faster"—to step away from highly controlled and comfortable Elizabethan-school ship-design practices and embrace a more fluid, adaptable, flexible, and much, much faster *Enterprise* ship-design philosophy.

## NOTES

1. Douglas Smith, *Carrier Battles: Command Decision in Harm's Way* (Annapolis, MD: Naval Institute Press, 2006), pp. xxvii–xxviii. Emphasis added.
2. John Jordan, *Warships after London: The End of the Treaty Era in the Five Major Fleets, 1930–1936* (Annapolis, MD: Naval Institute Press, 2020), p. 203.
3. Ibid., p. 204. Emphasis added.
4. Joel Holwitt, *"Execute against Japan": The U.S. Decision to Conduct Unrestricted Submarine Warfare* (College Station: Texas A&M Univ. Press, 2009), pp. 1–2, 31–34, 42–47.
5. Expanded from author's presentation, prepared with assistance from the USN Program Executive Office Ships staff, in David Lewis, "Remarks Delivered at ASNE Combat Systems Symposium" (Arlington, VA, 26 March 2012).
6. As discussed at length in David Evans and Mark Peattie, *Kaigun: Strategy, Tactics, and Technology in the Imperial Japanese Navy, 1887–1941* (Annapolis, MD: Naval Institute Press, 1997), pp. 370–83, and Malcolm Muir Jr., "Rearming in a Vacuum: United States Navy Intelligence and the Japanese Capital Ship Threat, 1936–1945," *Journal of Military History* 54, no. 4 (October 1990), pp. 473–85.
7. Raymond A. Bawal, *Titans of the Rising Sun: The Rise and Fall of* Yamato *Class Battleships* (Clinton Township, MI: Inland Expressions, 2010), pp. 68–71; Evans and Peattie, *Kaigun,* p. 373; Muir, "Rearming in a Vacuum," pp. 473–85.

8. Author's analysis developed from United States Strategic Bombing Survey, *Japanese Merchant Shipping* (Washington, DC: U.S. Government Printing Office, 1947); John Atkinson, *Imperial Japanese Navy WWII* (Bromley, U.K.: Galago Books, 2002); Robert Gardiner, Roger Chesneau, and Przemysław Budzbon, *Conway's All the World's Fighting Ships 1922–1946* (New York: Mayflower Books, 1980); Hansgeorg Jentschura, Dieter Jung, and Peter Mickel, *Warships of the Imperial Japanese Navy 1869–1945* (Annapolis, MD: Naval Institute Press, 1977); and Evans and Peattie, *Kaigun,* p. 383.
9. The capital ships permitted to be retained by the signatories are described in terms of tonnage in Treaty for the Limitation of Naval Armament, ch. II, pt. 1, 6 February 1922, T.S. No. 671.
10. The so-called London Treaty improved Japan's relative permitted ratios for cruisers and most types of minor vessels and auxiliaries and revised submarine and armament restrictions. The treaty expired in 1936 and Japan withdrew from negotiations for, and declined to sign, a follow-on treaty in 1936. Treaty for the Limitation and Reduction of Naval Armament, 22 April 1930, T.S. No. 830.
11. Bawal, *Titans,* pp. 48–49, 58; Evans and Peattie, *Kaigun,* p. 379; Mark Stille, *The Imperial Japanese Navy in the Pacific War* (Oxford, U.K.: Osprey, 2013), pp. 12–14, 16–17; Emily Goldman, "The Spread of Western Military Models to Ottoman Turkey and Meiji Japan," in *The Sources of Military Change: Culture, Politics, Technology,* ed. Theo Farrell and Terry Terriff (Boulder, CO: Lynne Rienner, 2002), pp. 57–59.
12. Evans and Peattie, *Kaigun,* p. 373; Stephen Roskill, *Naval Policy between the Wars,* vol. 1, *The Period of Anglo-American Antagonism, 1919–1929* (Barnsley, U.K.: Seaforth, 1968), p. 309.
13. Stille, *Imperial Japanese Navy,* p. 141.
14. Bawal, *Titans,* p. 184.
15. Ibid., pp. 97–98, 124–27.
16. The Japanese navy had six carriers (*Shōkaku, Zuikaku, Junyō,* and three light carriers), plus *Hiyō* fitting out, while the U.S. Navy had just three *(Saratoga, Hornet,* and *Enterprise).* James Belote and William Belote, *Titans of the Seas: The Development and Operations of Japanese and American Carrier Task Forces during World War II* (New York: Harper & Row, 1975), p. 133.
17. Sadao Asada, *From Mahan to Pearl Harbor: The Imperial Japanese Navy and the United States* (Annapolis, MD: Naval Institute Press, 2007), pp. 186, 240; Azar Gat, *A History of Military Thought: From the Enlightenment to the Cold War* (Oxford, U.K.: Oxford Univ. Press, 2001), pp. 698, 691.
18. Evans and Peattie, *Kaigun,* chaps. 2–6. Mahan adapted Jomini's theory of war to the maritime domain, as discussed in Gat, *History of Military Thought,* chap. 4, and as refuted on pp. 671–73, 676–80.
19. Evans and Peattie, *Kaigun,* p. 295.
20. Asada, *Mahan to Pearl Harbor,* pp. 240–41; Jordan, *Warships after London,* pp. 75–79, 287–90.
21. Trent Hone, *Learning War: The Evolution of Fighting Doctrine in the U.S. Navy, 1898–1945* (Annapolis, MD: Naval Institute Press, 2018), pp. 128–33; Frank Hoffman, *Mars Adapting: Military Change during War* (Annapolis, MD: Naval Institute Press, 2021), p. 60; Holwitt, *"Execute against Japan,"* pp. 63–67.
22. Jordan, *Warships after London,* pp. 221–27.
23. Jennifer K. Elsea and Richard F. Grimmett, eds., *Declarations of War and Authorizations for the Use of Military Force: Historical Background and Legal Implications* (Hauppauge, NY: Nova Science, 2009), p. 5.
24. Robert Kaufman, *Arms Control during the Pre-nuclear Era: The United States and Naval Limitation between the Two World Wars* (New York: Columbia Univ. Press, 1990), pp. 65, 137–78. See also Roskill, *Naval Policy,* vol. 1, pp. 327–28, and the U.S. ratification of extending prohibitions on unrestricted submarine warfare in the 1936 London Treaty in Stephen Roskill, *Naval Policy between the Wars,* vol. 2, *The Period of Reluctant Rearmament, 1930–1939* (Annapolis, MD: Naval Institute Press, 2016), p. 320. However, Hoffman points out that the U.S. war plan RAINBOW 5, approved on 19 November 1941, called for "[destruction of] Axis sea communications by capturing or destroying [trade] vessels." Hoffman, *Mars Adapting,* pp. 59, 286; see also Holwitt, *"Execute against Japan,"* pp. 45–47.

25. Holwitt, *"Execute against Japan,"* p. 1.

26. Clay Blair Jr., *Silent Victory: The U.S. Submarine War against Japan* (Annapolis, MD: Naval Institute Press, 1975), pp. 415, 551–54; Hoffman, *Mars Adapting,* pp. 69–76.

27. Lieutenant Commander Morton was a brilliant, aggressive captain, and under his command *Wahoo* became the most successful submarine in the Pacific Fleet, until its loss in 1943. Lieutenant Commander O'Kane transferred before *Wahoo*'s disappearance and went on to be the most successful submarine captain of the war, in command of USS *Tang.* See Stephen Rosen, *Winning the Next War: Innovation and the Modern Military* (Ithaca, NY: Cornell Univ. Press, 1991), pp. 130–47.

28. German U-boats sank 2,882 Allied ships totaling 14.4 million tons, peaking in 1942; U.S. submarines sank 1,314 ships totaling 5.3 million tons, and 95 percent of Japanese prewar merchant mariners were casualties, despite a slow start. However, Allied shipping capacity was so great that even these higher losses did not impede either military or civilian wartime supply needs decisively, while Japan's military and civilian shipping capacity effectively was annihilated. Blair, *Silent Victory,* pp. 878–79.

29. There is some dispute on this point; see Gary Weir, *Forged in War: The Naval-Industrial Complex and American Submarine Construction, 1940–1961* (Honolulu, HI: Univ. Press of the Pacific, 2000), p. 115.

30. John Jordan, *Warships after Washington: The Development of the Five Major Fleets, 1922–1930* (Annapolis, MD: Naval Institute Press, 2011), p. 153.

31. This discussion is derived from Norman Friedman, "Have We Been There Before? Launch/Recovery Lessons Learned from Carrier & Amphibious Ship Development" (remarks at "Launch and Recovery of Manned and Unmanned Vehicles from Surface Platforms: Current and Future Trends" conference, Annapolis, MD, 8 November 2005). See also Roskill, *Naval Policy,* vol. 1, pp. 324, 416–17, on the U.S. Navy's decision to convert its big battle cruisers, the Royal Navy's failure to do the same, and the resulting respective operational impacts.

32. Jordan, *Warships after London,* pp. 83–86, 91–97.

33. Author's analysis; P-12 introduced in 1927; T4M in 1928; F2F in 1934; BG-1 in 1934; BT-1 in 1935; SBU-1 in 1935; SB2U in 1937; F4F in 1940; SBD in 1940; and TBF in 1942. This does not count functionally obsolete aircraft that were introduced briefly. See Gordon Swanborough and Peter Bowers, *United States Navy Aircraft since 1911* (Annapolis, MD: Naval Institute Press, 1968), pp. 62–65, 310–13, 197–201, 193–94, 357–58, 397–98, 399–400, 205–10, 167–69, 213–16.

34. Per Jordan, "*Ark Royal* was arguably the best carrier laid down for the Royal Navy in the interwar period. . . . However, she was also a prime example of the extent to which 'ship' rather than aviation characteristics continued to dominate British carrier design during the 1930s. Although similar in size to the . . . *Yorktown* class, she operated fewer aircraft, had an aviation fuel capacity of 100,000 tons compared with 187,000 tons, and had hangars with low ceilings and narrow lifts that could not accommodate spread aircraft." Jordan, *Warships after London,* p. 91.

35. Ibid., pp. 84–86; Norman Friedman, *U.S. Aircraft Carriers: An Illustrated Design History* (Annapolis, MD: Naval Institute Press, 1983), pp. 65–70.

36. Friedman, *U.S. Aircraft Carriers,* pp. 77, 114; Jordan, *Warships after London,* p. 96.

37. Craig Symonds, *World War II at Sea: A Global History* (Oxford, U.K.: Oxford Univ. Press, 2018), pp. 270–74.

38. Bawal, *Titans,* p. 88.

39. Jonathan Page, "Flexibility in Early Stage Design of US Navy Ships: An Analysis of Options" (master's thesis, Massachusetts Institute of Technology, June 2011). From the abstract: "In this application, the model predicts that, on average, a flexible platform should not only cost less to build, but also reduce modernization costs by 9% per ship over its life cycle. Therefore, counterintuitively, building a less-capable ship with the flexibility to expand capabilities or switch missions actually provides greater expected utility during its service life."

40. James Holloway III, *Aircraft Carriers at War: A Personal Retrospective of Korea, Vietnam, and the Soviet Confrontation* (Annapolis, MD: Naval Institute Press, 2007), pp. xi–xiii. See Peter Sims, *Little Bets: How Breakthrough*

*Ideas Emerge from Small Discoveries* (New York: Free Press, 2011), pp. 13–14, 152, for his discussion of an incremental approach to innovation (i.e., "little bets").

41. Susan Ronald, *Heretic Queen: Queen Elizabeth I and the Wars of Religion* (New York: St. Martin's, 2012), pp. 25–35.

42. The "Willie Sutton rule" is named for an early-twentieth-century American bank robber's apocryphal remark to a reporter that he robbed banks "because that's where the money is," just as Spanish galleons were "where the money was" in sixteenth-century Europe. Susan Ronald, *The Pirate Queen: Queen Elizabeth I, Her Pirate Adventurers, and the Dawn of Empire* (New York: HarperCollins, 2007), pp. 26–37, 55–66; P. H. Colomb, *Naval Warfare: Its Ruling Principles and Practice Historically Treated,* Classics of Sea Power Series (Annapolis, MD: Naval Institute Press, 1990), pp. 26–27.

43. N. A. M. Rodger, *The Safeguard of the Sea: A Naval History of Britain, 660–1649* (New York: W. W. Norton, 1999), p. 207.

44. Galleys could not mount heavy cannon anywhere but at their bows or sterns, because they were too narrow either to absorb their recoil safely or to support the guns' weight abeam and, galleys being oared vessels, this midships space was occupied already by rowers. Julian Corbett, *Drake and the Tudor Navy: With a History of the Rise of England as a Maritime Power* (London: Longman, 1912), pp. 1, 8–10; Rodger, *Safeguard of the Sea,* pp. 212–13; John Guilmartin Jr., *Galleons and Galleys* (London: Cassell, 2002), pp. 158–60.

45. Geoffrey Moorhouse, *Great Harry's Navy: How Henry VIII Gave England Sea Power* (London: Weidenfeld & Nicolson, 2005), pp. 127, 130, 253–58; Corbett, *Drake,* pp. 29–30; M. Oppenheim, *A History of the Administration of the Royal Navy and of Merchant Marine Shipping in Relation to the Navy, from MDIX to MDCLX* (London: J. Lane, 1896; facsimile, 1961), pp. 52–60, 98–99.

46. Also called English "race-built" galleons. See Guilmartin, *Galleons,* pp. 160–62; Corbett, *Drake,* p. 352; Rodger, *Safeguard of the Sea,* pp. 204–20; and Oppenheim, *A History,* p. 126.

47. Oppenheim, *A History,* pp. 129–32.

48. This professionalization of the navy made it both less corrupt and more a national asset than a personal possession of the queen. See Rodger, *Safeguard of the Sea,* p. 230; Corbett, *Drake,* pp. 342–50; and Oppenheim, *A History,* pp. 144–52.

49. Rodger, *Safeguard of the Sea,* p. 270. For example, "one of [the] Armada captains relates that the English fired their heavy guns as quickly as the Spaniards did their muskets." Oppenheim, *A History,* p. 158.

50. The Royal Navy, in its modern form, would not be born for another century. Rodger, *Safeguard of the Sea,* pp. xxi–xxii.

51. Paul Johnson, *The Birth of the Modern: World Society, 1815–1830* (New York: HarperPerennial, 1991), p. 195. "Robert Fulton['s] . . . first patented boat, which had its trials on the East River on 9 August 1807, was described as 'an ungainly craft looking precisely like a backwoods sawmill mounted on a scow and set on fire.'"

52. James Baxter, *The Introduction of the Ironclad Warship* (Annapolis, MD: Naval Institute Press, 2001), chaps. 5, 10; Nicholas Lambert, *Sir John Fisher's Naval Revolution* (Columbia: Univ. of South Carolina Press, 1999), p. 75, chap. 4.

53. Paraphrased from Baxter, *Ironclad Warship,* p. 3. For background on the stability of technology before Trafalgar, see Roger Knight, *The Pursuit of Victory: The Life and Achievement of Horatio Nelson* (New York: Basic Books, 2005); for an overview of naval operations and engineering, see Harold Sprout and Margaret Sprout, *The Rise of American Naval Power, 1776–1918* (Annapolis, MD: Naval Institute Press, 1990); for a general naval discussion of the period with a focus on economic issues, see Paul Kennedy, *The Rise and Fall of British Naval Mastery* (Dublin: Ashfield, 1976); for a detailed discussion of the emergence of early steel battleships, see John Beeler, *Birth of the Battleship: British Capital Ship Design, 1870–1881* (Annapolis, MD: Naval Institute Press, 2001), and Theodore Ropp, *The Development of a Modern Navy: French Naval Policy, 1871–1904* (Annapolis, MD: Naval Institute Press, 1987).

54. The sad case of USS *Wampanoag* is applicable. It was designed in 1863 as a high-speed, steam-powered anti-Confederate commerce raider—but the U.S. Navy declared the commerce-raiding mission obsolete after the Civil War. Controversy over its sustainment

cost, advanced propulsion system, and suspect seaworthiness resulted in the ship's decommissioning in 1868—after eight months of service. Sprout and Sprout, *Rise of American Naval Power,* pp. 198–99; Don Leggett and Richard Dunn, eds., *Re-inventing the Ship: Science, Technology and the Maritime World, 1800–1918* (Farnham, U.K.: Ashgate, 2012), pp. 186–87.

55. Jordan, *Warships after London,* p. 166.

56. Both Jordan's *Warships after London* and his *Warships after Washington* contain numerous examples, particularly Japan's cruiser modernization in the 1930s. See Jordan, *Warships after Washington,* pp. 155–59, 166.

57. Adding new technology into ships with treaty-limited displacements required weight reductions in other areas, challenging ship designers and operational planners. Jordan, *Warships after London,* p. 165.

58. Ibid., pp. 204–205. Also, "When the time came for naval rearmament [after World War I] it was size rather than versatility that was the main objective of the building programme." D. M. Schurman, *The Education of a Navy: The Development of British Naval Strategic Thought, 1867–1914* (London: Cassell, 1965; repr. Malabar, FL: Robert E. Krieger, 1984), p. 188. This citation refers to the Krieger edition.

59. Smith, *Carrier Battles,* pp. 81, 127, 130; Lars Celander, *How Carriers Fought: Carrier Operations in WWII* (Philadelphia, PA: Casemate, 2018), p. 134. Similarly, USS *Enterprise* (CV 6) renewed its entire air wing in August 1941, first replacing biplane fighters with monoplane fighters and subsequently with folding-wing fighters in March 1942. See Barrett Tillman, Enterprise: *America's Fightingest Ship and the Men Who Helped Win World War II* (New York: Simon & Schuster, 2012), pp. 26, 56. Likewise, the next USS *Enterprise* (CVN 65) changed its air-wing configuration three times for its first two deployments. See Holloway, *Carriers at War,* pp. 184, 235.

60. Smith, *Carrier Battles,* pp. 128–32, 135–36. All four Japanese aircraft carriers sunk at Midway received their principal damage from American carrier-based dive-bombers.

61. In their case, deck loading, overhead height, ramp slope, ammunition storage, and troop berthing, among a few others.

62. Jeff Kline [Capt., USN (Ret.)] (Professor of Practice, Naval Postgraduate School), interview by author, 21 September 2021.

63. See Alexander Kossiakoff and William Sweet, *Systems Engineering: Principles and Practice* (New York: Wiley, 2002), pp. 5–14; Charles Wasson, *System Analysis, Design, and Development: Concepts, Principles, and Practices* (New York: Wiley, 2006), pp. 67–85; and Sandra Dewitz, *Systems Analysis and Design and the Transition to Objects* (New York: McGraw-Hill, 1996), pp. 14–20; as well as many other fine engineering texts.

64. The "detect-to-engage" sequence is the process by which a target is detected, identified, tracked, and then engaged by a weapon system. Aegis was novel for combining these processes into an integrated system, rather than having standalone radar, combat, and weapon systems.

65. Thom Shanker, "Missile Strikes a Spy Satellite Falling from Its Orbit," *New York Times,* 21 February 2008, nytimes.com/.

66. "Navy Abruptly Cancels New Class of Destroyer," *Columbus Dispatch,* 31 August 2008, dispatch.com/.

67. "The military services could all build a better mousetrap; the problem came when they had to go after different animals." Craig Cameron, "The U.S. Military's 'Two-Front War,' 1963–1988," in Farrell and Terriff, *The Sources of Military Change,* p. 134. Sims calls this "the illusion of rationality." Sims, *Little Bets,* p. 25.

68. Richard Danzig, *Driving in the Dark: Ten Propositions about Prediction and National Security* (Washington, DC: Center for a New American Security, September 2011).

69. Hence U.S. Defense Dept., *Operation of the Adaptive Acquisition Framework,* DoDI 5000.02 (Washington, DC: Office of the Secretary of Defense, 23 January 2020). On the framework: "According to Undersecretary Lord, the Department of Defense's (DoD) new approach, called the Adaptive Acquisition Framework (AAF), will be the 'most transformational change to acquisition policy in years, perhaps decades.' Recognizing that the defense acquisition system (DAS) for major systems 'rarely enabled speed' and had design-to-delivery take up to eight years, Lord looks to adopting under AAF 'best practices' from industry

that would enable the AAF to bridge gaps between design and fielding to 'deliver capability to our warfighters faster' and, by making the acquisitions process 'move at the speed of relevance,' ensure responsiveness to the National Defense Strategy's (NDS) prescription that the US prepare for great power competition with Russia and China." Jack Deschauer, "Attention: Commercial Startups—Major DoD Announcements Regarding 'Adaptive Acquisition Framework' and Support for Emerging Technologies," *National Law Review,* 9 October, 2020, natlawreview.com/.

70. Michael Horowitz, *The Diffusion of Military Power: Causes and Consequences for International Politics* (Princeton, NJ: Princeton Univ. Press, 2010), chap. 7; David Barno and Nora Bensahel, *Adaptation under Fire: How Militaries Change in Wartime* (New York: Oxford Univ. Press, 2020), chap. 9. Also, per Scharre, "more than thirty nations already have defensive supervised autonomous weapons" and "sixteen nations already have armed drones." Paul Scharre, *Army of None: Autonomous Weapons and the Future of War* (New York: W. W. Norton, 2018), pp. 4, 369. Brose explores some speculative operational examples and impacts of autonomy in war as well. Christian Brose, *The Kill Chain: Defending America in the Future of High-Tech Warfare* (New York: Hachette Books, 2020), chap. 9.

71. Deschauer, "Major DoD Announcements."

72. Page, "Flexibility."

73. Robbin Laird, "Aboard USS *Ford:* More Weapons, More Launches, Faster & Safer," *Breaking Defense,* 25 November 2020, breakingdefense.com/.

74. Kai-Fu Lee, *AI Superpowers: China, Silicon Valley, and the New World Order* (New York: Houghton Mifflin Harcourt, 2018), p. 44; Eric Ries, *The Lean Startup: How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses* (New York: Crown Business, 2011), p. 294. Understand *minimum viable capability* as an initial set of capabilities that provide operational value to the user but also permit and enable the development of future improvements; derived by the author from U.S. Defense Department concepts *minimum viable product* and *minimum viable capability release,* as relates to software acquisition, in U.S. Defense Dept., *Operation of the Software Acquisition Pathway,* DoDI 5000.87 (Washington, DC: Office of the Secretary of Defense, 2 October 2020), p. 22.

75. Charles Stanton, *Medieval Maritime Warfare* (Barnsley, U.K.: Pen and Sword, 2015), chap. 7; Gillian Hutchinson, *Medieval Ships and Shipping* (Leicester, U.K.: Leicester Univ. Press, 1994), pp. 5–10.

76. Terry Terriff, "U.S. Ideas and Military Change in NATO, 1989–1994," in Farrell and Terriff, *The Sources of Military Change,* pp. 98–101.

77. This makes the Danish navy a classic "early adopter," as discussed in Sims, *Little Bets,* pp. 131–33.

78. H. Hornhaver, "STANDARD FLEX Distributed Architecture Combat System," *Naval Engineers Journal* 107, no. 3 (May 1995), pp. 41–48; Hartmut Manseck, "The Royal Danish Navy 'Absalon' Class Flexible Support Ship," *Naval Forces* 27, no. 3 (2006), pp. 99–107; Hans Hesselberg [Capt., RDN], "RDN Modularity" (remarks at ASNE Day 2013: Engineering America's Maritime Dominance, Arlington, VA, 21 February 2013).

79. "Structure of the Navy," *Danish Defence,* updated 1 September 2020, forsvaret.dk/en; Jeremy Stöhs, "Into the Abyss? European Naval Power in the Post–Cold War Era," *Naval War College Review* 71, no. 3 (Summer 2018), pp. 20–21; Janne Matlary and Øyvind Østerud, *Denationalisation of Defence* (Farnham, U.K.: Ashgate, 2007), pp. 130–31.

80. "While Denmark could be characterised as a *'defensive, non-provocative actor'* during the cold war, it can be claimed that in the post–cold war period Denmark has emerged as a *'civilian/military offensive actor,'* and since 9/11 could be considered as a *'strategic offensive actor.'*" Matlary and Østerud, *Denationalisation,* pp. 118–19.

81. Kurt Birger Jensen [Rear Adm., RDN] (Admiral Danish Fleet), interview 2006; Stöhs, "Into the Abyss?," p. 29; Kristian Haumann [Cdr., RDN], "Experiences and Operational Lessons Learned" (remarks at ASNE Flexible Ships Forum, 17 November 2016), pp. 9–12.

82. Edward Lundquist, "Royal Danish Navy Growing into New Missile Defense Role," *Defense Media Network,* 15 January 2020, defensemedianetwork.com/.

83. Andrew Chuter, "Britain Goes with Danish Design for New Navy Frigates," *Defense News,* 12 September 2019, defensenews.com/; "Steel Cut for First Type 31 Frigate—HMS *Venturer,*" *Navy Lookout,* 23 September 2021, navylookout.com/.

84. Megan Eckstein, "What the U.S. Navy Could Learn from Danish Frigate Design," *USNI News,* 5 March 2015, news.usni.org/; Per Hesselberg [Capt., RDN], interview by Vago Muradian, *Defense & Aerospace Report,* 29 November 2016, defaeroreport.com/.

85. Ellen Lord (former Under Secretary of Defense for Acquisition and Sustainment, U.S. Defense Dept.), interview by author.

86. Hornhaver, "STANDARD FLEX."

87. Defined by the Danish navy as ninety days. Hesselberg, "RDN Modularity."

88. See, for example, cost, manning, maintenance, and mission-module-delay issues in Ronald O'Rourke, *Navy Littoral Combat Ship (LCS) Program: Background and Issues for Congress,* CRS Report (Washington, DC: Congressional Research Service, 17 December 2019).

89. From the author's experience, the "rule of two" in shipbuilding is never to introduce more than two new major technologies in any new ship class, flight, or baseline. The U.S. Navy violated this rule of thumb in the *Seawolf,* LCS, *Gerald R. Ford,* and DDG-1000 classes with negative impacts, but did so in the *Spruance, Ticonderoga,* and *Arleigh Burke* shipbuilding programs with good outcomes.

90. Thomas Kuhn, *The Structure of Scientific Revolutions* (Chicago: Univ. of Chicago Press, 1962), pp. 10–22.

91. "Army Cancels NLOS-LS Missile System; LCS Implications Could Be Big," Military.com, 23 April 2010; Carlo Munoz, "Navy to Arm LCS with New Missile System," *Breaking Defense,* 20 October 2011, breakingdefense.com/.

92. Ronald O'Rourke, *Navy Frigate (FFG[X]) Program: Background and Issues for Congress* (Washington, DC: Congressional Research Service, 26 June 2020).

93. Ronald O'Rourke, *Navy* Constellation *(FFG-62) Class Frigate Program: Background and Issues for Congress* (Washington, DC: Congressional Research Service, 29 September 2021), pp. 19–20.

94. Kevin Smith [Capt., USN], "New Construction & Modernization Issues, Challenges, and Opportunities as the Navy Migrates to a Digital Environment and Digital Engineering" (remarks at American Society of Naval Engineers Virtual Technology, Systems & Ships Symposium, 27 January 2021, virtual).

95. David Larter, "Do the Earliest *Arleigh Burke*–Class Destroyers Still Have Legs? The US Navy Thinks So," *Defense News,* 13 January 2021, defensenews.com/.

96. Ryan Pickrell, "A US Navy Carrier Strike Group Is Deploying with Advanced 5th-Generation F-35C Stealth Fighter Jets for the First Time," *Business Insider,* 22 August 2021, businessinsider.com/.

97. Gidget Fuentes, "First Marine F-35B Combat Deployment Hints at New Roles for Amphibious Ready Group," *USNI News,* 27 February 2019, news.usni.org/.

98. Ronald O'Rourke, *Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress* (Washington, DC: Congressional Research Service, 24 February 2021). Existing Aegis SPY-1D systems already have been "modularized" to support requirements for the Aegis Ashore Phased Adaptive Approach (PAA). *Department of Defense Appropriations for 2012: Hearings before the Subcomm. on Defense of the H. Comm. on Appropriations,* 112th Cong., p. 164 (2012) (statement of Ray Mabus, Secretary of the Navy). However, Aegis-equipped ships have not been modified to support the installation or change-out of those module designs.

99. In the thirty-eight years that Aegis ships have been in commission, there have been five major versions of the SPY radar and ten major hardware or software baselines, for a total of fifteen major upgrades. This averages out to one major upgrade every two and a half years, or roughly one upgrade per nominal ship-deployment cycle. Had any of the eighty-nine Aegis ships built for the U.S. Navy been of an *Enterprise* design, those ships could have been outfitted with the most modern radar and the most capable combat system continuously throughout their service lives. Each deployment by such surface combatants would have fielded the Navy's most modern and capable war-fighting systems, just as the Navy's aircraft carriers have done for the past eighty-seven years.

100. See, for example, prior work cited in Page, "Flexibility," and Jonathan Mun, "Flexible Ship Options" (master's thesis, Naval Postgraduate School, 1 October 2018).

101. Tim Harford, *Adapt: Why Success Always Starts with Failure* (New York: Farrar, Straus, Giroux, 2011), p. 84.

102. Megaproject research identifies poor risk assessments as using EGAP (everything goes according to plan) principles rather than MLD (most likely development) or even worst-case-scenario methods to assess project risk. See Bent Flyvbjerg, Nils Bruzelius, and Werner Rothengatter, *Megaprojects and Risk: An Anatomy of Ambition* (Cambridge, U.K.: Cambridge Univ. Press, 2003), pp. 80–85, 138. Also see the closely related discussion of Flyvbjerg's "reference class forecasting" and the planning fallacy in Daniel Kahneman, *Thinking, Fast and Slow* (New York: Farrar, Straus, Giroux, 2011), pp. 249–51. This article is itself grounded in reference class forecasting, using past aircraft carrier life-cycle operational technology performance as a predictor for a new, future surface ship life-cycle operational technology performance model.

103. However, having done it once more or less by accident, the U.S. Navy proceeded with the idea of developing purpose-built, carrier-based bombers and flew a prototype before the end of the war. Thomas C. Hone, Norman Friedman, and Mark D. Mandeles, *Innovation in Carrier Aviation,* Newport Paper 37 (Newport, RI: Naval War College Press, 2011).

104. Edward Miller, *War Plan Orange: The U.S. Strategy to Defeat Japan, 1897–1945* (Annapolis, MD: Naval Institute Press, 2007), chap. 29.

105. Arthur Herman, *Freedom's Forge: How American Business Produced Victory in World War II* (New York: Random House, 2012), pp. 85–106.

106. "We have to be comfortable being uncomfortable." Sims, *Little Bets,* p. 45.