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The Great Race: Innovation and Counter-Innovation at Sea, 1840-1890

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Key Points

- The Great Race was history's first revolution in military affairs that was recognised as such by contemporaries. It was a race that was driven less by the 'pull' of naval strategic requirements than the 'push' of technological opportunity and hence introduced technological innovation as a new and key variable in the international security equation.

- Naval innovation and counter-innovation occurred at two different levels: there was the Anglo-French rivalry, with France usually being the innovator and Britain the 'quick follower,' and there was the competition between increasingly thicker and more shell-resistant armour, and progressively more destructive gun power.

- The Great Race transformed the warship from a balanced offensive-defensive platform into a vulnerable too expensive-to lose offensive platform which, it turned out in 1914-18, saddled both sides with the wrong fleets-for-the wrong war.

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Introduction: **La Gloire** *and the New French Revolution*

In 1858 the British Admiralty reviewed the balance of power at sea between the Royal Navy and its traditional European enemy, France. Two "threats" in particular drew their Lordships' attention – one, old and familiar but already belonging to a bygone era; the other new, yet already recognised in Britain and elsewhere as the harbinger of a very different set of rules of power at sea. The old threat which concerned the Admiralty was the widening "timber gap." A comparison of supplies of ship-grade timber showed that the French had stockpiled more than 133,000 loads, whereas the British held a mere 70,000 loads, barely enough to build four line-of-battleships, 11 frigates, and 13 corvettes. The Admiralty then turned its attention to one the 'few questions relating to the sufficiency of the Navy… more important than the means of securing an adequate supply of ship-building timber.'[1] The question of particular interest was the report prepared by a certain Lieutenant Colonel R. Claremont following his visit to the French Navy's building yard in Toulon. While visiting the yard, he wrote, he had observed the construction of a steam-powered frigate. She was quite large, the timbers appearing 'quite as large and heavy as those of a three-decker.' He was told, Claremont wrote, that the armament would include 36 heavy guns, most of them rifled 50-pounders, 'which will throw an 80 lb. hollow percussion shot.' The ship's motive power would evidently come from an 800-900-horsepower steam engine 'cased in iron.'[2]

It was the latter in particular that concerned the men in charge of the Royal Navy. Steam power was not new, nor was building ships with wrought iron hulls. What was new was that the French had evidently managed to bring these two technologies together in a single *large* warship. Small iron warships had been built since the late 1830s, but extensive gunfire tests on both sides of the English Channel had convinced naval professionals that iron plating was no more resistant to cannon fire than oak, and that when penetrated, iron produced more dangerous splinters than wood.[3] As a result, the handful of iron steam frigates built in the 1840s were converted to auxiliaries. The Claremont report suggested the French had found a solution. Had they perhaps found a way to reduce the penetrability of iron by combining it with some other material? Claremont had witnessed French gun-firing trials, and his observations were not re-assuring. He wrote:

> I did not exaggerate when I talked to you of the success of their experiments, firing at iron plates to cover the side of a ship; they blazed away at twenty metres, 50-pounders, first, with hollow shot, which went off into dust; then with solid shot, which was also smashed; and finally, with cast-steel shot, which was split, but also split the plates, without, however, penetrating.[4]

The man responsible for the design and construction of the Royal Navy's warships, Surveyor of the Navy, Sir Baldwin Walker, sought to downplay the importance of what he called the French 'experiment' - iron-sided ships would be so heavy that they would likely be unstable in heavy seas; they required very large steam plants, and finally, iron hulls would likely lose out to improvements in gunnery.[5] Yet, the French evidently thought otherwise. The Admiralty's *Estimates* noted 'so convinced do (French) naval men seem to be…of the irresistible qualities of these ships, that they do not mean to lay down another ship of the line, as they say that in ten years they will have become quite obsolete.'[6]

The French assessment proved right, of course; by 1870, the wooden ship of the line had been relegated to history. In its place had come the machine-age products of the 'Great Race' – the competition during the second one-half of the nineteenth century between the increasingly destructive power of bigger and heavier guns, and efforts to create shot-resistant armour. This is an account of the Great Race – its technological roots and the dynamics of innovation and counter-innovation which, in the end, drove fleets into a technological cul-de-sac.

The Technical Roots of the Great Race

The ship Claremont had seen under construction became known as *La Gloire*, the first large warship to combine an armoured hull, steam propulsion and explosive shell-firing guns into a single platform. The world 'combine' is important, because as has already been suggested, the individual components – steam, iron hulls and exploding shellfire – had been in common usage for many years already. Navies and commercial shipping had used steam and iron ships almost since the beginning of the nineteenth century, and exploding shells had been used in land warfare for centuries. Indeed, they had been used at sea quite extensively two centuries earlier. Which, of course, prompts the question: if steam, iron hulls and even shellfire by themselves were not particularly novel in the 1850s, what was it that catalyzed their synthesis at that time? The key, it seems, was the invention of a workable screw propeller. This device, along with associated improvements in marine engineering – boiler making, gearing, lubricants, seals, etc. – offered a far more efficient and less vulnerable alternative to the principal means of marine steam propulsion so far, the paddlewheel.

Steam and Paddlewheels

Like so many inventions, the idea of using steam to power paddlewheels and thus self-propel, appears to have sprung from the fertile minds of different inventors at approximately the same time. The first experiments took place in the late eighteenth century in places as far apart as France and the United States. The first paddler for war-making purposes was built by Robert Fulton in 1814 for the defence of New York harbour against the British fleet. The ship, *Demologos*, never saw action, because its first trial came after the War of 1812 had ended.

By the late 1820s, commercial paddle steamers had become fairly common in American and European coastal waters. The first naval steamers appeared at about the same time, but they were used mainly as harbour tugs or for other auxiliary duties. There were a couple of reasons for this somewhat reluctant start; both served to delay the exploitation of the steam engine for naval purposes until the arrival of the screw propeller. The first problem was the low power and poor fuel efficiency of the early single-cylinder reciprocating engines; the second was the unsatisfactory performance of the propelling paddles in a seaway. When more powerful engines became available in the 1830s, the Royal Navy ordered its first two, 1,000-plus ton steam paddle frigates.[7]

By the early 1840s, paddle frigates with displacements equalling that of a sailing ship-of-the-line, i.e., around 3,000 tons, had been built. Yet, because of the presence of the bulky side paddles, they could not mount the large number of broadside guns of a first-rater. The solution was to arm the ships with a few of the heaviest and longest-range guns then available, and place them on both ends. Some enthusiasts at the time believed that, come a shoot-out with a traditional ship-of-line, the steam frigate's combination of auto-manoeuvrability and long range artillery would more than compensate for its inferior volume of firepower.[8] Firing trials told a different story. It turned out that, even under ideal conditions – clear sky, wind light, smooth sea – the highly trained gun crew of the Royal Navy's gunnery school ship, HMS *Excellent* managed to land only about one out of ten projectiles on a stationary target 3,000 yards away. The hitting rate became much better when the range was cut in half, but the firing in this case was done by a fixed land-based battery.[9] It goes without saying that the results would have been worse if the target had been moving and 'uncooperative.' The implication was clear: if a ship was going to rely on a few instead of many guns, and fight at stand-off ranges, then much greater accuracy was needed than had been necessary for a line-of-battle ship firing point blank barrages. Until this happened, the traditional sailing ship-of-the-line with its long banks of cannon remained the centrepiece of naval power.

Steam paddlers had other problems that limited their usefulness as naval combatants. Their wooden construction meant there were limits on the weight of gunnery and machinery that could be installed. The early steam plants in particular were extremely heavy and bulky contraptions. Take, for example, the British-built *Gorgon*, which has been called the 'first true fighting steamship.'[10] Laid down in 1835, she was fitted with a 350nhp (nominal horsepower) power plant and could stow 380 tons of coal. The engine was of a new design. Called a 'direct-acting' engine, it reputedly weighed 60 tons less and occupied less space than the first-generation 'side lever' plants.[11] Its overall weight, including boilers, coal boxes, shafts, etc, still amounted to 277 tons, or almost one-sixth of the ship's 1,610 ton displacement. If a full load of coal is added, *Gorgon*'s power plant accounted for about 40 per cent of her displacement.[12] Another way of looking at the 'design impact' of contemporary paddlewheel engines is by noting that up to 40-plus per cent of the ship's length was typically devoted to power, i.e., machinery and coal. This may not seem particularly problematic, until it is recalled that the great paddle wheels and most of the propulsion machinery were housed *above* the waterline. This caused two problems: first, it made the ship highly vulnerable to what is called today a 'mobility kill'; next, the bulky paddle wheels had the effect of dividing the ship into two 'fighting halves' – the fore and aft gun decks, separated, as in the case of *Gorgon*, by some 60 feet of topside vitals. One can readily imagine the difficulty this posed for organizing some sort of centralized fire control.

The early steam paddlers were still made of wood. As David Wood has written, Nelson's wooden walls may have had a 'heart of oak,' but structurally they were weak ships.[13] They tended to hog and heave in a seaway, and the heavy, vibrating machinery put further strains on the ship's timbers. It followed that as long as ships were built of wood, and barring the creation of much lighter and less bulky propulsion plants, steam paddlers could not grow to accommodate the armament of a full-fledged man o' war. But even a transition to iron could only be part of the solution, so long as mobility and endurance relied on paddlewheels and marine engines, which, according to one report, required up to seven pounds of coal to produce one horse power for one hour.[14] Furthermore, only one-half of the generated horsepower might be delivered to the shaft.[15] From the perspective of the naval officer, this meant that range and endurance were extremely limited, and that too much space and weight were taken up by coal instead of guns, ammunition and other naval stores.

The way the paddlewheels operated added further inefficiencies. To begin with, they were vulnerable to gunfire. Bernard Brodie in his classic study of the era's naval technological revolution exaggerated only a little, when he wrote how these 'huge and cumbrous affairs could be utterly disabled by the explosion of a well-placed shell.'[16] Another, perhaps bigger drawback which plagued the ship in peace *and* war was the paddles' 'variable immersion problem.' This had to do with the difficulty of keeping both wheels immersed at a depth where they performed best. Doing so was difficult for two reasons. First, the wheels' 'dipping' depth changed constantly as the ship burned up its load of coal and became lighter. On top of that, with each roll in rough seas, one or the other wheel would be out of the water for some time, so that the system worked at only half its efficiency.[17] When the paddle steamer's different vulnerabilities and inefficiencies are summed up, it becomes evident why this form of propulsion for seagoing ships, particularly ships of war, was a technological *cul-de-sac*. The screw propeller opened up an escape route.

'A Sort of Screw or Worm'

The screw propeller too was one of those devices whose birth had been in gestation for centuries. Its basic design is usually credited to Archimedes, hence the term 'Archimedan type screw.' Dozens of names are associated with the modern screw propeller, but most accounts have settled on the Swedish-born John Ericsson and the Englishman Francis Petit Smith. Both obtained patents in the same year, 1836. The world's first sea-going screw-driven steamship, appropriately named *Archimedes*, was launched on the Thames River two years later. The 232-ton ship was a private venture, built specifically to demonstrate the virtues of the new device. Extensive tests and trials over the next few years impressed Admiralty observers enough for the Royal Navy to launch its own screw steamer, *Rattler*, in 1843. It was used for a series of competitive experiments, which culminated in a highly publicized tug-of-war with the paddle wheeler *Alecto* in 1845.

The screw propeller turned in a superior performance which served to reinforce the Admiralty's favourable attitude toward the device. It was underwater and therefore protected from enemy shot. The connecting shaft to the machinery was low, so that the engineering spaces, too, could be entirely below the waterline. Machinery vibration was less – which was important for the still wooden ships – and power was delivered more efficiently, which meant that lighter machinery could be installed and the consumption of coal reduced. Most important perhaps from the viewpoint of admiralties, the elimination of the cumbersome paddle wheels meant that broadside-firing ships, i.e. line-of-battle ships, could now be machine-powered. In 1846, the British backfitted two ships-of-line with steam plants, thereby creating the world's first 'screwliners.'

In common with all steam-powered vessels at the time, the early British screw liners retained their masts and rigging. But whereas the smaller vessels used steam for their main propulsion and sail for auxiliary purposes, the screwliners relied on sail first and steam secondarily. It was left to the French to introduce the world's first steam battleship designed and built from-the-keel-up to use steam as the main propulsion system. The ship, *Napoléon*, was the brainchild of the man who was arguably the most gifted and most innovative warship designer in the nineteenth century, Dupuy de Lôme (more on him later). First proposed in 1847, *Napoléon* was launched in 1850 and completed for sea duty in 1852. The British promptly hastened to complete work on their own first purpose-built screwliner, the *Agamemnon*. For the next nearly ten years, until the arrival of *La Gloire*, the wooden screwliner remained the centrepiece of a naval race of sorts between France and Britain. Britain had the advantage in numbers, but the French carried on a tradition of superior design and individual ship performance.[18]

The Paixhans Gun Revolution

It seems ironic that at the same time that the screw propeller made it possible to preserve the familiar shape of power at sea, the new screwliners were being re-armed with a weapon that would be their undoing. The culprit: the explosive shell-firing gun. The weapon itself had been known in land warfare for centuries, but was not adopted at sea until the 1830s. Much of this transition can be attributed to the proselytizing activities of a French artillery officer by the name of Henri-Joseph Paixhans. His extensive combat experience during the Napoleonic wars, including a tour of duty with a coastal battery, had prompted Paixhans to think about a more effective way of combating enemy warships. In 1821, he published a pamphlet, entitled *Nouvelle force maritime*.[19] In it, he claimed that it was possible to build small vessels, crew them with a handful of inexperienced soldiers, and yet have enough power to destroy the largest line-of-battle ship. The secret: large calibre guns using shellfire. The weapons became popularly known as 'Paixhans guns.'

Paixhan's major work, published in 1822, set forth his ideas in greater detail. France's navy, he said, had made a number of important innovations in recent years. But as long as the balance of power between his country's navy and that of the British depended on numbers, they were not enough to produce a revolutionary change – Britain's numbers would retain the advantage. The solution for France, he wrote, was to replace existing naval ordnance with guns of the same weight, but bored to larger calibres and used for horizontal shellfire. Since such weapons would be much more destructive than existing gunnery, it followed that their carrying platforms had to change as well. Paixhans' proposed a *nouvelle force maritime*, made up of frigate-size and 'high-speed' smaller vessels with crews no larger than 30-50 men. They would be steam-propelled and armed with a few standardized large-calibre shell-firing guns. Since it was to be expected that the opponent would follow suit and also adopt shell-firing guns, it was necessary that the New Navy's ships be protected by a metal *armure*.

Phaixans went out of his way to assure his audience that he had, 'innovated nothing, invented nothing, and almost changed nothing.' All he had done was to pull together the different elements that, when given attention, showed that the ship-of-the-line 'system' had no future. It goes without saying that the target of Paixhans New Navy was the British fleet, but he was realist enough to acknowledge that the old adversary would react and seek to preserve its superiority. But, he claimed, even when the British followed suit and adopted their own new weapons, France's naval transformation would still be worthwhile. The product would be cheaper than a line-of-battle fleet and, most important, would need fewer experienced seamen. This, Phaixans promised, would neutralize Britain's traditional advantage of a large seafaring population, so that 20,000 sailors, 'born and nurtured on the ocean,' would no longer have the power to dictate the law to the entire world.[20]

Technically speaking, Paxhains was right – neither steam, nor armour, nor shell-firing naval gunnery were novelties *per sé*. Explosive shells had even been used at sea quite extensively during the seventeenth century. But when they were, they were fired by specially-designed bomb ketches in which more than the usual care was taken to prevent accidental explosions and fires.[21] It was the latter danger that had so far kept navies from incorporating shell guns as standard equipment. But if Phaixans did not invent the technologies for a new way of war at sea, he certainly *innovated* their application toward that end. His innovation was to visualize how a series of existing technologies could be integrated into a coherent system-of-systems that would upset the existing order at sea. History proved him wrong on a number of counts – shellfire and armour did not displace the capital ship (although the debate continues whether perhaps history took a wrong turn); machine-driven ships, even small ones, were not cheaper than ships-of-the-line, and experienced crews became even more important after the age of sail. But the essentials of his image of the fleet-of-the-future, including his expectation of progressively larger and powerful guns and the difficulty of protection against them, proved to be right.[22]

It has been suggested by one author that the French reaction to Paixhans' ideas was less than enthusiastic; that 'in general his propositions were just too revolutionary to be taken in one dose.'[23] It is true that the French naval administration would not embrace Paixhans' entire package, but key individual pieces had a very positive reception. The proposal to standardize shipboard guns was accepted immediately; trials with Paixhans' new gun began in 1824. The results prompted a strong recommendation by the *Académie des Sciences* that the weapon be adopted gradually throughout the navy. The first guns were placed on ships in the same year; fleet wide introduction took place in 1837.[24]

Paixhans' idea of protecting ships with iron plating was also taken in hand. In 1833, France began firing trials against heavy wooden targets faced with iron.[25] In sum, even though the French naval hierarchy was unwilling to accept Phaixans' forecast of the end of the line-of-battle ship, it showed an admirable willingness to put new ideas to the test, and let experimentation, not institutional predilections, be the judge

The British adopted the Phaixans gun in 1839. They did so reluctantly, for it was Whitehall's golden rule 'to follow and overtake rather than to initiate.'[26] Yet, had Britain failed to keep pace, wrote one author many years later, 'her material would be rendered suddenly obsolete, her maritime power would shrivel; and the power of France would be augmented to such a degree that the defeat of these islands might at last be encompassed.'[27]

The Crimean War and the End of the Wooden Walls

Screwliners, armed with Paixhans guns, dominated the naval scene for about one decade. Even while they were being built, designers on both sides of the English Channel, but especially in France, recognised that they could only be a temporary solution to the problem of how to combine, in a single platform, the new forms of firepower, mobility and protection. Dupuy de Lôme, for one, recognized early on that a permanent solution called for radically different ships. In 1845, at the age of 29, and while the working for France's *Ministère de la Marine* as a *sous-ingénieur*, he submitted his first proposal to build a steam-powered ironclad – a 28-gun ship with a displacement of 2,366 tons and in which the vitals, namely the propulsion plant, would be protected by a belt of laminated iron about 6½ inches thick.[28] The project was stillborn, because the French naval leadership, like their rivals across the Channel, were still not satisfied with the durability and the resistance of iron to shell fire. Dupuy de Lôme then turned his talent to drawing up the plans for the *Napoléon*. Three years after the ship went to sea, she and her likes participated in the only war the screw liners ever fought – the Anglo-French war against Russia, commonly known as the Crimean War. This conflict spelled the end of the line for the wooden warship.

The Russian navy's destruction of the Turkish fleet at Sinope in 1854 which precipitated the Crimean war was the first and vivid demonstration of the vulnerability of wooden ships to shellfire. French Emperor Napoleon III was impressed enough to persuade his own country's navy and his British allies that using wooden ships to bombard Russia's fortifications in the Baltic and on the Crimean Peninsula was too risky. He proposed – and the British agreed – to build steam-propelled floating batteries, arm them with a few heavy Paixhans guns, and protect them with armour to withstand shellfire. In October 1855, three of the French floating batteries joined 13 ships-of-the-line to bombard a Russian fort on the Kinburn Peninsula at the mouth of the Bug and Dnieper rivers. The vessels' 4-inch wrought iron cladding withstood numerous shell hits without appreciable damage; their own guns succeeded in silencing the Russian defences. The episode was a milestone in naval history: it marked the first time that genuine armoured warships engaged in battle, thereby successfully violating Nelson's maxim to never engage in duel with land-based fortifications. The event spurred a flurry of interest in shallow draft combatants suitable for from-the-sea fighting. This triggered the creation of yet another novel ship type – the coast defence ship or, in France, the *garde côte*.

In some ways, these first generation floating batteries can be thought of as the antecedents of the U.S. Navy's 'arsenal ship' plan of the 1990s.[29] But just as ships fit for operations on the open ocean remain the principal preoccupation of American naval planners today, so the most important task for French and British designers 150 years ago was to solve the problem of vulnerability of *seagoing* warships. Again, it was Napoleon III's intervention that set the stage for the transformation of France's wooden ships-of-the line into ironclads. In October 1854, he proposed that the new ironclad floating batteries be complemented by an ironclad steam fleet. The *Commission supérieure centrale*, which had been formed in 1843 to oversee the creation of a, still wooden, steam fleet, paid heed. In 1857, it announced that, in light of the progressively greater penetrative power of rifled guns, all work on wooden warships was to be halted, and that all men o' war would henceforth be ironclads.[30] There was still the problem of fabricating the right kind of armour plating – strong enough to resist shell fire, yet light enough to not cause an excessive power requirement – but, by the late 1850s, the basic conditions for the most important revolution in naval affairs since the introduction of the ocean-going sailing warship, were in place. Dupuy de Lôme, now promoted to *Directeur du Matérial*, was the man chosen to lead the revolution. He would design not only the world's first fast ironclad frigate, but also the world's first seagoing ironclad *fleet*. His *La Gloire*, following on the heels of *Napoléon* and the armour-clad batteries at Kinburn, firmly established France's innovative lead. Then and for several decades afterward, there was 'no country where more ingenuity and audacity have been displayed in the designing of warships.'[31]

French Lions among British Sheep

La Gloire was laid down at the Toulon shipyard 1858. She was the lead hull in a group of four ironclads, the others being *Invincibl*e, *Normandie*, and *Couronne*. The last ship was different, for unlike the first three, which had wooden hulls covered with four inches of iron plating, the *Couronne* was based on a hull made entirely of iron. Some sources have proposed that

France's limited iron producing facilities forced Dupuy de Lôme to still use wooden hulls.[32] This is not plausible. France's production of pig iron in 1858 reportedly amounted to 872,000 metric tons. Britain produced more than four times as much, but surely the French output would have been enough to come up with the 2,000 or so tons it would have taken to build an all-iron *La Gloire*![33] It is at least as likely that the decision to build the first three ships with iron clad wooden hulls, and the fourth with an all-iron hull, was reflective of Dupuy de Lôme's evolutionary design philosophy. He believed that, given the many technical uncertainties that still needed solving, the early phases of the fleet's transformation should allow for experimentation with alternative design concepts and building methods.

It is also important note that the decision to build the *La Gloire* and her sister ships was very much a *deliberate* and *strategic* decision. The French – unlike the British – embarked on a program of naval innovation in accordance with a defined set of strategic goals and associated force structure. Made public in 1857, the program called for a navy that included these components: (1) a combat fleet of the most powerful and fast ships for use in European waters; (2) a war transport fleet composed mostly of the older 'mixed' steam-and-sail wooden ships-of-the-line; (3) special combatants for the defence of ports and harbours; and (4) sailing ships to provide economical transportation in time of peace.[34]

As work progressed on the first four ironclads, the keels for two more, evolutionary designs, the *Magenta* and *Solferin*o, were laid down in 1859. In the same year, on November 24, *La Gloire* was launched; *Normandie* and *Invincible*, were in the spring of the following year. *La Gloire'*s performance at sea was impressive, prompting Dupuy de Lôme to declare her steaming and navigational qualities to be superior to those of the best steam-powered screwliners. He felt that the technology and building experience were now in hand to take the next step and make a wholesale transition to an all-ironclad fleet. He specifically proposed that France immediately embark upon the building of 10 more seagoing ironclads and 11 armoured floating batteries, all to be completed within 18 months. When this goal was reached, France would have a fleet of 16 seagoing ironclads, nine coastal defence ironclads, and 11 floating armoured batteries. The 1860 program was promptly approved – nine armour plated but wooden-hull ships and one all-iron vessel were ordered, as were seven floating batteries. The 'great revolution in naval construction' had begun to unfold.[35]

The new fleet would be expensive, but Dupuy de Lôme assured the *Ministère de la Marine* that the ships' revolutionary impact on the balance of power at sea more than justified their price tag. He promised that, if only one of this new 'species' of warships were to be, '…*lancé au milieu d'une flotte entièr vaisseaux de bois, y serait avec 36 pièces, comme un lion au milieu d'un troupe de moutons*.'[36]

The British paid attention. The reports by Claremont and others compelled the head of the Board of Admiralty, Sir John Pakingham, to revise Britain's warship building policy of converting the existing fleet of sailing ships-of-the-line to screwliners. Sir John was 'very anxious…mortified and vexed,' yet determined 'of using every effort to recover the ground which had been lost.'[37] Sir Baldwin Walker, too, was forced to recant his earlier scepticism about the seaworthiness of the French ironclads. Although he maintained that the screwliner was still the fleet's capital ship, Walker felt that the time had come to match the French effort. In a now famous statement of British policy on technical innovation, he announced:

> Although I have frequently stated that it is not to the interest of Great Britain – possessing as she does so large a navy – to adopt important change in the construction of ships of war which might have the effect of rendering necessary the introduction of a new class of costly vessels, until such a course is forced upon her by the adoption by Foreign Powers of formidable ships of novel character requiring similar ships to cope with them, yet it then becomes a matter not only of expediency, but of absolute necessity. This time has arrived. France has now commenced to build frigates of great speed with their sides protected by thick metal plates, and this renders it imperative for this country to do the same without a moment's delay.[38]

The upshot was the Royal Navy's first 'reply ship', HMS *Warrior*. The Great Race was on.

The Great Race: Institutionalising Innovation

Commissioned in the summer of 1861 with a displacement of over 9,000 tons, *Warrior* was three times larger than the typical wooden line-of-battle ship, and nearly twice as large as *La Gloire*. She was more heavily armed and, most important, differed from the French ship in that she was made entirely of iron. Because she was launched before France's *La Courone*, *Warrior* can claim to be the first true seagoing ironclad warship.

The creation of *La Gloire* and *Warrior* marked a milestone in many regards, but two in particular stand out. First, it marked the synthesis of steam, iron, and shellfire – the three key technologies that, according to Bernard Brodie, changed the ship-of-the-line 'with its towering masts…uncorrupted by funnel or fire box,' into a 'monster of steel carrying huge ordnance, propelling itself by steam, capable of hurling destruction upon antagonists miles away.'[39] Secondly, the British tit-for-tat response set the stage for what came to be known as the 'Great Race' – the competition over the next three decades or so between the development of increasingly powerful and destructive naval gunnery and the attempt to create shot-resistant armour. It was a rivalry fought out mainly, though by no means exclusively, between France and Britain; it also amounted to the first conscious arms race in modern history.[40] This phenomenon alone is enough to mark this period as a 'revolution in military affairs.' And it was a very special arms race at that, for as has been pointed out by a number of authors, it marked the first time in human history that an arms race could be not only a race to build up matériel, but also a race to *innovate*.[41]

This last observation in particular touches on the unprecedented nature of this era of military-technological innovation, namely the awareness, for the first time in history, that the world, including the world of the military, was changing – and changing rapidly. One contemporary observer made this comment on the nature of change at the time: 'There is perhaps no period in the history of the human race which has change so numerous, so startling, so far reaching, as the present century, or we might almost say the half-century in which we live.'[42] Rapid technological innovation in the means of war was itself a brand new, indeed revolutionary, phenomenon. True, other revolutionary changes in the means and methods of warfare had come before – firearms, artillery, the fully rigged sailing man o' war, and others, but most had been so slow and gradual, that successive generations of soldiers and sailors had rarely been conscious they were witness to the creation of a new form of warfare.[43] The second one-half of the nineteenth century marked the first time that contemporaries were aware that tomorrow's wars would be fought with weapons different from yesterday's. As early as 1864, only five years after *La Gloire* had made its appearance, a Dutch admiral wrote a treatise on the political and strategic implications for his country of what he called the 'revolution in naval warfare.'[44] And even earlier, in 1858, British artillery expert, General Sir Howard Douglas, predicted that the change from sail to steam power 'is a vast and sudden change in the means of engaging action on the seas, which must produce an entire revolution in naval warfare.'[45]

The transformation of the material means of sea warfare alone was dramatic enough to warrant the label 'revolutionary.' But what set this era of change particularly apart from what had gone before was the *rapidity* of change. Continuous and rapid military-technological innovation is routine today, but for the Victorian naval professional, the notion that technology, or rather, being on the cutting edge of technology, might henceforth spell the difference between victory and defeat, was an entirely novel one. This is not to say that the sailing ship-of-the-line and the guns it carried had not constantly been improved upon – they had. But until the widespread introduction of steam in the late 1840s, change had been slow, predictable, and in accordance with principles of design and construction that had changed little in over two centuries.[46] Sir Nathaniel Barnaby, who was one of the British navy's chief warship designers during this time, reported how he had found that few of the patents granted between 1618 and 1810 for improvements related to ships, were worth recording.[47] Progress in the design and construction of naval gunnery, too, had been slow and devoid of technical breakthroughs. There had been advances since the Napoleonic wars in the calibre and power of individual pieces, but until 1840, cast-iron smooth bore guns firing solid shot with a – theoretical – maximum hitting range of 1,000 yards, were still the rule. In sum, the sailors and gunners that manned the two-deckers of the Anglo-Dutch wars of the seventeenth century would have had little difficulty adjusting to the fleets of the 1830s.

Writing after his retirement, Barnaby commented (in 1902), that '(t)here is but little trace…in naval affairs to-day…of the conservative temper (that) has marked naval matters for ages.' It was a change, 'so remarkable.'[48] And so it was, but for more reasons than Barnaby presumably had in mind: the rapid expansion and proliferation of scientific and engineering knowledge, with the attendant ability to create novel combinations of offensive and defensive power, had upset old and familiar balance of power calculations. In the past, the defence planner's calculus of war had been relatively straightforward: strength and weakness were mainly a function of numbers, be they soldiers in the field or ships at sea. True, there was the matter of the admiral's (or general's) *coup d'oeil*, but in the end the mark of military genius was the knack to marshal the largest number cannons (or muskets) at the right place and right time. In the past, weeks or even months of diplomatic tensions commonly preceded active military hostilities. This normally afforded plenty of time to mobilise armies, take warships out of ordinary, refit them with masts, rigging and guns, and find crews.[49] Volatile technological change revolutionized this calculation by introducing the possibility of sudden, war-winning *qualitative* asymmetries between fleets.

The new technological insecurity had important consequences for the way competitors had to keep abreast of one another's activities. In the past, when fleets prepared for the eventuality of a war in which likes fought likes, there had been few secrets to keep or ferret out. Since warships were impossible to hide, it took little specialised intelligence gathering for both sides to be reasonably confident of the other's strengths and weaknesses. And again, strength at sea meant *numbers*, especially, of course, numbers of line-of-battle ships. It was fairly easy, moreover, to confidently predict the potential opponent's future strength by merely keeping watch over the numbers of ships kept in ordinary or on the building stocks. It followed that governments and their navies had no pressing need for peacetime intelligence organisations.[50] As an aside, it is important to keep in mind in this connection that, during peace, the major naval powers of the pre-machine age era normally kept only a fraction of their principal combatants at sea; for economic reasons, most were kept in ordinary, i.e. tied up, without sails, rigging, or crews. Only when war threatened, would more ships be taken out of ordinary and commissioned. Rapid and unpredictable material change provided the impetus for the systematization of naval intelligence and analysis as a continuous activity in war *and* peace. All major – and many minor – navies followed in the path of the Royal Navy, when it formed a Naval Intelligence Department (NID) in 1870.

New strategic uncertainties were confounded by a host of novel technical dilemmas. Designing and building ironclads, especially in the 1860s and 1870s, was very much an experimental activity with very few scientific design principles, never mind *strategic* principles, to guide the process. It required the integration of a host of novel technologies and materials that had never been tested in combat, and which had to be combined into architectural and structural arrangements that were alien to the tried-and-true design and construction practices of the sailing era. Discarding the traditional way of shipbuilding risked losing safe engineering practices. For example, because of the much less obvious relationship between weight and volume of a piece of iron than of wood, it became easy to install an iron stiffener that was 25 per cent overweight. As a result, the early ironclads tended to be heavier than estimated, with some being delivered with a draft two feet or more than their design.[51] This might not matter if the ship had a high freeboard, but if it did not, the result could be disaster.[52]

And then there was the matter of strategic purpose. In theory at least, large weapons systems such as warships are designed and built in the image of one or more strategic purposes. Again in theory, those purposes should reflect the unique goals and interests of the building nation. The designers of the early armourclads, especially on the British side, appear to have had only the scantest of guidance in this regard. It would have helped to know, for example, whether the new machine-age vessels would be preoccupied mainly with near-shore defensive operations off one's own ports and harbours, or more distant offensive action against a hostile coast. Short of explicit guidance, the French and British navies built both. Indeed, the evidence is compelling that the shape of fleets that evolved after *La Gloire* and *Warrior* was less the result of strategic and operational requirements set by the nations' naval leadership, than the product of technological opportunity.

French Innovation and British Counter-Innovation

La Gloire and *Warrior* shared one characteristic – both used 4½ inches of iron armour to protect the hulls. But there was an important difference also: the protective belt on the French vessel extended from stem to stern, whereas only 56 per cent of *Warrior*'s hull was covered. The decision to leave the ship's bow and stern unprotected was motivated by the - unfounded - concern that all-round protection would make the ship unstable.[53] In the long run though, the concentration of armour on only a portion of the ship became a portent of things to come: as increasingly powerful guns became available, the escalating cost - in terms of both money and weight – of providing all-around armour compelled designers to leave progressively larger portions of the ship unprotected. *Warrior*'s armour (exclusive of the teakwood backing) weighed 950 tons for a weight fraction relative to overall displacement of about ten per cent. By the late 1870s, the weight of armour accounted for some 30 per cent or more of a ship's overall displacement.

The ordnance and protective armour arrangement of the British ironclad was a clue to other design trends as well. One was the re-distribution of shipboard firepower away from large numbers of medium-calibre guns, set along the length of the ship, to a concentration of fewer large calibre weapons inside thickly armoured central batteries or 'casemates.' An important drawback of this arrangement was the extremely limited ability to bring fire to bear fore and aft. One radical solution was the revolving turret, or 'revolving battery tower.' Ironclads with rotating turrets had been used in the American Civil War - most famously in the encounter between the turreted *Monitor* and *Merrimack* casemate ship at Hampton Roads – but these were not seagoing vessels. Ships designed for operations in relatively calm coastal waters had a low freeboard, which enabled them to maintain stability despite the turrets' heavy weight. But small freeboards were unsuitable in a seaway, whereas raising it and yet maintaining stability, meant building a much larger ship. In any case, as long as ships still carried masts, sails and rigging, they could not take full advantage of the turret's wide arc of fire. Britain's attempt to combine turrets and full rigging on a seagoing warship ended in disaster, when a ship thus built, the *Captain,* capsised under full sail.

The French, too, recognised that the broadside or central battery arrangement held no promise for further development, and that the turret or some kind of rotating gun system was the only alternative worth pursuing. Dupuy de Lôme – again – is usually credited for instituting the 'French solution' of arraying guns *en barbette*. It was a solution driven, in part, by the concern that central battery and casemate systems dangerously over-concentrated the ship's firepower in a single area. The barbette was basically a circular armoured redoubt enclosing a turntable and the gun's (or guns') ammunition tubes. Unlike the turret, this was an open arrangement in which the gun itself was elevated to fire over the armoured enclosure.[54] This exposed the gun and crew to splinters, but to the French at least, this was well worth the price for a rotating gun system that, thanks to a much reduced weight, could be installed on ships with a high freeboard. The French began installing barbettes alongside central batteries in the early 1860s; in 1877, the transition was completed, when the first large seagoing ironclad with guns protected only by barbettes (the *Amiral Duperré*) was launched.

The first British effort at copying the barbette system occurred in the late 1870s, when the *Temeraire* was fitted with one on each end. What distinguished the system from the French one was that each barbette was served by a hydraulic system, which made the gun disappear below the firing parapet for re-loading. The system worked alright, but it could not accommodate the increasingly larger and heavier guns that were becoming available. Consequently, the *Temeraire*'s barbettes became one-of-a-kind, and the British went back to building turret ships. But there was a limit on the growth of the turret as well. That limit was effectively reached in1881, when the *Inflexible* went to sea with four 16-inch muzzle-loading guns housed in two turrets. The guns weighed 80 tons a piece and the turrets 750 tons each. Even though each turret had diameter of nearly 34 feet, this was still not enough space to do the ammunition loading inside.[55] The problem was a peculiarly British one, and it had to do with the British choice of guns.

In the early 1860s, the Royal Navy had followed the example of the major Continental fleets and begun to replace its muzzle-loading guns with breechloaders. The transition was short-lived, however. A series of mishaps, due to poor construction, prompted the decision, in 1865, to revert to muzzle-loaders. As far as the Royal Navy was concerned, these were entirely adequate. A good gun crew could load and fire a muzzleloader as fast or faster than a breechloader, and rapidity of fire, not range, was the navy's first priority. The breechloader's main advantage was that it allowed for a longer barrel and therefore greater muzzle energy. This translated into greater shooting ranges, but the Royal Navy of the 1870s had little use for long-range gunfire if it could not be delivered accurately.[56] Rapid-firing guns, capable of penetrating at short ranges, made more sense. Accordingly, for the next 15 years the British literally stuck to their muzzle-loading guns, while the Continental navies continued to improve upon the breech-loaders.

Two developments compelled the British to reconsider. First, by the mid-1870s, the new French and German-made breechloaders were clearly superior to the latest British muzzleloaders in terms of muzzle velocity, range, and penetration power. The problem that had prompted British rejection of the breechloader 15 years earlier, namely the disastrous tendency for the gun to be fired before the breech was fully closed, had meanwhile been solved. Since, high velocity guns required long barrels, the only practical solution was to build breechloaders. It was not that long-barrelled muzzle-loaders could not be built, but their long run-in and out between firings meant they could not be housed in barbettes. The British adopted the French-designed breech-closing system and launched their first ship with breech-loading guns in barbettes (the *Collingwood*) in 1887 - ten years after the *Amiral Duperré*.

A Menagerie of Unruly and Curiously Assorted Ships

The evolutionary character of the French transition from the central battery ship to the all-barbette ironclad was characteristic of the generally more systematic progression of French warship design. While one could speak of a distinct French 'style,' British warships built between the 1860 and '80s stood out for a heterogeneity that has been described as a 'menagerie of unruly and curiously assorted ships.'[57] One reason was the lack of consensus on the fleet's strategic purpose. Was its main role to protect Britain against a French invasion? Blockade enemy ports and harbours? Protect trade, or perhaps defend the empire's colonies? Different strategic priorities called for different ships. Shallow-draft monitors or casemate ships were suitable for coastal defence and attack; lightly armoured cruisers were appropriate for the defence of trade; and so forth. Unclear about the Navy's principal roles and missions, the British built a hodgepodge of one offs, many of them so-called 'reply ships,' built in response to the most recent French (or Italian) innovation or the latest European war scare.

The accelerating pace of naval-technological innovation added to the confusion. By the late 1860s, the poor accuracy of gunfire contributed to the belief that the ram was the weapon of the future. At about the same time a far more exotic weapon, the torpedo, began to enter navies. As soon as the new weapon was put on a small high-speed craft, called torpedo boats, the problem of ship defence took on an entirely different dimension: for the first time in history, a capital vessel had to defend itself against something that was not another capital ship. In an editorial in May 1877, the London *Times*, wondered, 'whether our magnificent ironclad fleet is not liable to be paralysed by means of little things which almost any Government could afford to construct.'[58]

The asymmetric danger of torpedo boats prompted the addition of quick-firing guns, but it was recognised before long, that the big ships needed the protection of an equally speedy torpedo boat interceptor, the forerunner of the modern destroyer. This move basically acknowledged that, for the first time since their creation, ships-of-the-line could no longer defend themselves. For fleet planners and warship designers, the big ship's loss of defensive autonomy signified that planning and designing a new ship now had to be done with reference to some agreed concept of a balanced fleet.

There was very little about the British navy of the 1870s that reflected such a concept. Oscar Parkes, who authored the standard reference work on the evolution of the British battleship, explained the absence of planning of any sort as follows:

> …it must be remembered that the essentials of naval policy, strategy, tactics and ship design were not yet regarded as a matter for close study or experiment. Our naval needs had never been properly formulated; there was no department charged with either the study of attack and defence, naval intelligence, or defence of our seaborn trade; naval manoeuvres were unknown; and no large-scale experimental tests were ever carried out.[59]

The idea that individual warships ought to be built and armed in accordance with some sort of overarching *fleet* concept embedded in an agreed strategic purpose, did not exist. Instead, wrote one late-nineteenth century commentator, 'what was really dealt with was what weight of gun would penetrate a certain thickness of armour; and what thickness of armour would resist the projectiles of a certain weight of gun.'[60] In this connection, there is little evidence to link the evolution of British warship design and armaments during this period to specific, navy generated, requirements. The transformation from smoothbore muzzleloaders to rifled breech-loading weapons is a case point. The Royal Navy of the mid-1860s was not interested in the higher energy and longer ranges that could be had with rifling and breech-loading. The service was quite satisfied that its 6-ton 100-pounder was just about the heaviest and highest-velocity gun it could possibly need. ‘So far as the navy was concerned,’ wrote Colomb, ‘there were no grounds for pushing things further.’[61] Bigger and heavier guns required larger platforms; more powerful guns also generated a need for thicker belts of armour, which again added to the size of ships. This connection between gun weight and ship size was one reason why many naval officers were critical of the trend toward monster guns of 100 tons and more. Many preferred ‘handy’ ships with medium-calibre guns. Critics of the bigger-is-better trend charged that the Navy had become the victim of a ‘crowd of inventors, designers, and manufacturers, all (of whom) let loose with their inventive and constructive powers…each of them intent on his own point, and none of them under such control as could harmonise their work with that of others.’[62]

If technology was driving the Navy into a direction it did not always want, this was the consequence, in part, of its own failure to spell out the direction it *should* go. Writing in the late 1880s, Sir Edward Reed, who had overseen the navy’s building program during the 1860s, offered this rather revealing explanation why the Navy owned a collection rather than fleet of ships. Because of the diverseness of Great Britain’s sea-going interests – protect the coast against invasion, commerce, the empire, coaling stations and so forth,

> …(H)er navy must be eclectic types, the exact instrument for any expected operation being always at hand; her maritime administration must be comprehensive; and her preparations ever such as will anticipate and surpass that of all her rivals. Enormously armoured battle-ships may be economically wrong, but while other countries build them so must she.[63]

Reed’s statement is interesting for a couple of reasons. First, his call for an ‘eclectic’ fleet is symptomatic of the state of strategic confusion at the time over what exactly the Royal Navy was expected to do, or for that matter, what the Royal Navy expected of itself to do. Depending on prevailing public fears – or at least those in Parliament – the Navy built monitors for coast and harbour defence whenever there was an invasion scare, cruisers to protect commerce and distant stations, or heavy armourclads for European waters to offset the latest French entry in this class of warships.

As far as the French threat was concerned, this had effectively ceased to exist with France's defeat at the hands of Prussia in 1870 and the subsequent rise of a unified Germany. There might still have been a handful of committed Francophobes, but after 1870 no responsible British political or military leader still looked to the French navy as a plausible future adversary. Nevertheless, the innovation race continued with a momentum of its own. This is implied in Reed's reference to the necessity for large and expensive warships as long as others acquired them. Before 1870, the British had good reason to interpret French technological innovation at sea as evidence of a new, more dangerous phase in a long history of rivalry and military conflict; the British reaction during this period could reasonably be interpreted as threat-driven. Afterward however, wrote Colomb, the real pressure for continuous innovation came not from foreign navies, but 'from the inventor acting in powers that were outside the navy, forcing it to change its mind in spite of itself.'[64] Another contemporary critic of British shipbuilding policy at the time, Thomas (later Sir Thomas) Brassey, agreed that the navy's 'reply ships' had little or nothing to do with the country's true maritime needs, but were mostly 'conceived under the influence of international rivalry…(and) to gratify the public.'[65] According to Brassey, the best that could be said for the creation of increasingly expensive, but also more vulnerable ships of 'large and unwieldy dimensions,' was that Britain had 'no choice in the matter.' Ironically, many French and Italian naval officers shared the scepticism of their British colleagues with respect to the bigger-is-better trend. But they, too, were trapped in the technological and competitive *cul de sac* plaintively hinted at by Brassy: as long as others had the capacity to build the behemoths, there was no choice but to meet them 'on equal terms.'[66]

The "Feverish Evolution"

La Gloire and *Warrior*'s 4½ inches of iron plate protection marked a brief moment in the era of machine-age fleets, when resistance to shellfire outclassed the gun's destructive power. Yet, even as the ships were being completed, heavier guns with greater penetrative power were already being tested on both sides of the Channel. By 1865, French and British warships had to be protected by six or seven inches of armour. Five years later, nine inches had become the norm, and by the end of the 1870s, 14 inches or more were common. The use of iron for hull armour reached its peak with the British *Inflexible*. Laid down in 1874, but not completed for another seven years, the ship's central citadel was covered by no less than 24 inches of iron. The turrets were protected by nine inches of steel-faced armour overlaid on iron plating seven inches thick. Whereas the *Warrior*'s 950 tons of iron protection had taken up about ten per cent of her overall displacement, the *Inflexible*'s armour weighed 3,275 tons, thereby accounting for some 28 per cent. Yet the portion of the ship protected by armour was getting increasingly smaller. Sixty per cent of the *Warrior*'s hull had been protected, but only 30 per cent of the *Inflexible* – only the area that contained the vital spaces, such as guns, ammunition and machinery, benefited. Even so, when *Inflexible* was launched, a next generation of guns could already penetrate even the two feet of iron covering the citadel. At this rate, predicted the French navy's *sous-ingénieur* M. Marchal, one-half of the ship's displacement would soon be devoted to armour.[67] Since this was unacceptable – if for no other reason than cost – it seemed to many commentators at the time that the only solution was to give up on armour altogether and rely on speed and guns for defensive protection. One who suggested this was Marchal's colleague, *sous-ingénieur* P. Dislère. In a series of articles written in 1873, he calculated that only 54 of the worldwide total of 318 ironclads of all types were protected by the minimum of 12 inches of iron needed to resist shellfire from a 12-inch calibre gun fired at a distance of 2,000 yards.[68] Yet, he pointed out, guns capable of penetrating 20 inches of armour were already on the drawing board! It followed, wrote Dislère, that 'we consider all the weight that's being employed to protect the ship as a complete waste'; that consequently, armour was 'destined to disappear from the side of our naval combatants.'[69]

On the other side of the Channel, an Admiralty committee agreed that, 'we appear now to be closely approaching a period when the gun will assert a final definitive superiority.'[70] But it was not prepared to draw the French conclusion and de-armour ships altogether. The committee's reasoning was interesting.

All the arguments against trying to keep up with the increasing destructiveness of the guns by adding more and more tons of armour were true – it amounted to an 'enormous dead weight;' it was very expensive, and it did not guarantee protection.[71] Nevertheless, if it came to a duel between an armoured and an unarmoured ship, the 'former has, and must have, an immense advantage in being able to penetrate the sides of her adversary at a distance at which she herself is impenetrable.' The committee therefore recommended that only the fleet's 'first ranks of ships' still receive the protection of heavy armour – others, cruisers, for example, would have to do without.[72]

The continued evolution of the armourclad might well have been cut short had it not been for the invention of the Bessemer process and other methods for producing large quantities of low-cost steel. Steel is basically a superior variety of iron. It has the same elastic quality as wrought iron but has the added benefit of hardness. This makes steel a particularly attractive material for the ship-building industry where the weight of the vessel and the space left for cargo are critically important. France's steel production in the mid-1870s was only about one-fourth of Britain's, yet the French Navy was the first to take advantage of steel's superior strength-to-weight ratio.[73] In 1872, the keel was laid for the *Redoubtable*, the first armoured warship to make extensive use of steel. Three years later, the shift was made to all-steel ship construction, and the year after, the French Schneider firm made history, when it produced a 22-inch steel armour plate with a ballistic resistance superior to its iron competitors. It took seven years for British yards to follow the precedent of the *Redoubtable* and build the – partially steel - *Colossus* and *Edinburgh*. It would be another ten years before the British shipbuilding industry completed the transformation from iron to steel, and warships were built of all-steel armour.[74] During those years it was forced to compensate for the brittleness of British-made steel by cementing steel plating to an iron back plate and call it compound armour.

The French navy had meanwhile continued to experiment with ways to make steel stronger and tougher. The efforts paid off in 1889, when the Schneider concern added nickel to produce nickel-steel armour. Tests showed a 30 per cent improvement in resistance over iron, meaning that a 10-inch nickel-steel plate resisted the same energy as a 13-inch iron plate. In the terminology of armourers, the Schneider plates had a figure of merit (FOM) of 1.3 Further improvements came rapidly. First, 'Harveyizing' (so-named after the American inventor Hayward Augustus Harvey) steel increased the FOM to about 2.0. Next, Krupp-cemented ('KC') armour was introduced. It raised the FOM to about 2.3 to 2.7, and in some cases, as high as 3.0. In sum, between the mid-1870s and mid-1890s, the change from iron to KC steel armour effectively tripled the resistance of armour to perforation by shellfire.[75]

The transition from iron hulls and armour to steel by no means equalled the revolutionary impact of *La Gloire*. The fact though that the French were the first to make this change highlights a pattern of French *innovation* and British *emulation*. At first sight, it seems surprising that British warship builders turned to all-steel construction and armouring years after their French colleagues. It should be recalled that a similar lag marked Britain's introduction of steel guns and shells.[76] The delay seems surprising for it was in Britain after all, where, thanks to Henry Bessemer's patent in 1856, the large-scale and economical production of steel, the so-called Bessemer process, was invented. One author at least has suggested that Britain's sluggishness can be attributed to the Admiralty's scepticism.[77] Others have suggested that Britain's heavy investment in ironworks made manufacturers loathe to give up a legacy industry. In any case, their Lordships had good reasons to be hesitant about embracing all-steel construction, for British Bessemer-made steel was notorious for its uneven quality and tendency to break up.[78] French-made steel was superior because it was produced by way of a different process, named after its inventors, Siemens-Martin. It was more expensive than Bessemer steel, but it was also more homogeneous and could be manufactured closer to specification. This meant that Bessemer steel was adequate for use in railroad tracks, for example, but that plating and custom works, such as guns, required the purer Siemens-Martin process product. Frustrated with the inferiority of home-produced steel, Sir Nathaniel Barnaby, the Royal Navy's chief constructor visited the Creusot furnace in France in

1874 in order to learn of the French secret first-hand. Impressed with the results, he took the unusual step of ordering French-made steel for the Royal Navy's first all-steel ships - two dispatch vessels.[79]

If the destructive power of naval gunnery had remained constant, then the armour of a warship built in the early 1890s would have weighed about one-third of its predecessor's built in the1870s. But this did not happen; armour continued to account for 25 per cent or more of the vessel's overall weight. And the reason was a simple one: improvements in the warship's offensive capabilities continued to outpace innovations benefiting the defence. In fact, the gap widened. Why this was so is hinted at in a pre-World War I textbook on warship construction. Noting how, 'at the present time…the attack is superior to the defence,' the author attributed the 'marvellous perfection of modern artillery' to the combination of 'workers in three distinct fields of science:' chemistry, metallurgy, and optics.[80] The first discipline produced progressively more powerful and efficient propellants; the second applied the progress made in armour to the creation of high-grade steel gun barrels, capable of handling the high stresses produced by more powerful propellants; and the field of optics gave gunners their first-ever means for stand-off 'precision' fire. Improved shell designs were a fourth reason why the old ideal of the balance offensive-defensive warship had become a thing of the past. Chilled-iron-tipped shells for use against armour – the so-called Palliser shell – had been in use since the late 1860s, but sinking a ship still relied mainly on the 'racking' effect of landing a series of heavy blows with the aim of causing the armour plate to cave in. This changed in the early 1880s, when the 'capped' armour-piercing shell made its debut; it was designed to punch *through* the armour and sink the ship from the inside out, so to speak.[81] The upshot was that every improvement in defensive armour was matched or overtaken almost immediately by advances in the gun's offensive penetrative power. Table 1 shows this trend during the half-century or so that separated the launching of *Warrior* and the introduction of the 13.5-in calibre guns that armed the Royal Navy's super dreadnoughts of World War I. The gun characteristics are British, but they are representative of the overall trend in naval gunnery during this era. It highlights the fact that, starting with the Mk. V

9-in. muzzleloader of 1865, artillery consistently out-performed the heaviest armour afloat at the time. To put this in perspective, every capital ship launched after *La Gloire* and *Warrior* was sinkable by its own guns!

Table 1: Evolution of Gun Penetrative Power vs. Armor Resistance, 1865-1910

Gun Caliber	Year of Design	Gun Weight, tons	Projectile Weight, lbs.	Muzzle Velocity, ft/sec	Penetrative Power	Armor Thickness
9-in.	1865	12	253	1,440	10” iron at 1,000 yds	6” iron
10-in.	1868	18	406	1,379	12” iron at 1,000 yds	9” iron
12-in.	1871	35	707	1,390	15” iron at 1,000 yds	12” iron
16-in.	1878	80	1,684	1,590	15” compound armor at 1,000 yds; 22” iron at 2,000 yds	24” iron
16.25-in.	1885	110.5	1,800	2,087	19” compound armor at 2,000 yds	18” compound armor
13.5-in., 30 cal.	1888	67	1,250	2,016	17” compound armor at 2,000 yds; 12” KC at 3,000 yds	20” compound armor
12-in., 35 cal.	1894	46	850	2,367	14.5” KC at 3,000 yds; 18” Harvey 3,000 yds	9” Harvey
12-in., 40 cal.	1903	50	850	2,760	20” KC at 2,000 yds; 16” KC at 15,000 yds	9” Harvey
12-in., 45 cal	1904	58	850	2,725	17” KC at 3,000 yds	11” KC
13.5-in., 45 cal.	1910	75.4	1,250	2,700	22.9” KC at 3,000 yds	12” KC

Note: The numbers under ‘Armor Thickness’ are typical of the weight and type of armor plating in use at the time the pertinent gun was designed.

Sources: Alan H. Burgoyne, Ed., *The Navy League Annual*, (London: John Murray, 1911), Table WW, pp. 267-77; Sir William Laid Clowes, *The Royal Navy: A History from the Earliest Times to the Death of Queen Victoria*, Vol. III, (London: Sampson Low, Marston and Co., 1903), pp. 44-48; Capt. S. Eardly-Willmott, *The Development of Navies During the Last Half-Century*, (London: Seeley and Co., 1892); Fred T, Jane, *The British Battle-Fleet: Its Inception & Growth Throughout the Centuries*, (London: S.W. Partidge & Co., 1912); Oscar Parkes, *British Battleships “*Warrior*” 1860 to “*Vanguard*” 1950: A History of Design, Construction and Armament*, (New and rev. ed. Hamden: Archon Books, 1970).

It is important to note that the numbers in Table 1 reflect contemporary estimates of armour and gun performance. Those estimates used the results of carefully controlled experimental firings and then applied various algorithms to calculate likely performance at fighting ranges. Guns and armour plating were typically tested at ranges of a few hundred yards. Those were realistic ranges during the 1860s; even two decades later, ships were not expected to engage at more than 2,000 yards. By the mid-1890s, however, this number had doubled and before the end of the century distances up to 10,000 yards became possible.[82] Of course, the ability to fire a 1,000-pound projectile on a 5-mile ballistic path and to actually hit an object are two very different things, especially if the target is small and does not stay in one place![83] It was only in the early 1890s, when some 30 years of experimental one-off types had finally given way to the construction of standardised, multi-unit classes of ships, that navies called for the development of accurate range finding instruments.[84]

The Inveterate French Innovators

In his classic study of the beginnings of the ironclad era, James Phinney Baxter, 3rd commented that, '(A)mong naval powers the weaker have a more obvious interest in revolutionizing naval warfare than have their stronger rivals.' Conversely, should the side that enjoys superiority at sea take the lead in introducing radically novel capabilities, 'it runs the risk of converting its existing fleet into junk and giving its rivals a fresh start with the slate wiped clean.'[85] The point was a familiar one during the American Revolution in Military Affairs debate of the 1990s – does it make sense for the technologically most advanced military power in the world today, i.e., the United States, to introduce means and methods of warfare that might diminish its legacy forces to obsolete junk and give competitors an opportunity to catch up? Phinney Baxter's proposition that the weaker power has a stronger incentive to innovate has an important caveat, though, which is that being first may not matter much if the innovator lacks the resources needed *sustain* the more favourable military balance it has created. Given that a weak-strong relationship between competitors is normally a function of an imbalance of resources to begin with, it is likely that a weaker innovator will enjoy a short-lived advantage at best

France's attempt to escape from its traditional naval inferiority *vis-à-vis* Britain by way of radical technological innovation, and change the 'rules of the game,' is a vivid demonstration. For some 20 years, French ingenuity in such diverse areas as ship design, artillery, and steel production, allowed it to build a series of warships which, in terms of innovative design, engineering and overall architecture, generally led their British counterparts. Broadly speaking also, the French ironclad fleet during the first 20 years after *La Gloire* was marked by a much greater degree of homogeneity than was the case on the other side of the Channel. The difference may stem partly from the fact that the French had a much longer and institutionalised tradition than the British in the scientific design of warships. One reason why French sailing men o' war had long been admired for their sea keeping qualities, was that naval architecture had been part of the curriculum of French naval schools since the beginning of the seventeenth century. Most theoretical treatises on ship design, in both France as well as abroad, were French. In Britain, by contrast, a School of Naval Architecture was set up only in 1811, but it was not long before it was closed again, ostensibly because the head of the Admiralty at the time, Sir James Graham, had concluded that science was of little use in naval ship building, and that any experienced naval officer was perfectly qualified to be in charge of the Navy's warship design bureau. It took another 30 years before the School was re-opened and was eventually merged with the newly established Royal Naval College in Greenwich outside London.

The difference between the French and British approaches at grooming their naval architects was symptomatic of two very distinct pedagogical philosophies: French engineering, including that of ships, was deductive and theory-based, whereas the British prided themselves on a more experience-based and pragmatic approach.[86] The aspiring French naval architect of the nineteenth century spent four years of rigorous study at what was then the world's finest institution of scientific and technical education – the *École Polytechnique*. The 'Poly' was the French state's training ground for different branches of engineering – roads and bridges, mining, canals, artillery and, of course, shipbuilding. After two years of general theoretical studies, a student set on joining the corps of the *Génie Maritime* would spend a third year studying the design of marine engines and a fourth on ship design calculations. During those last two years, he would get practical experience by spending his summers at one of the French naval dockyards. Upon graduation, the student typically joined the navy's design bureau as a junior constructor.[87]

The British system was starkly different. Until the re-establishment of the Royal School of Naval Architecture in 1863, the Navy's constructors were groomed on-the-job in the Navy's or privately-owned dockyards. Thus, almost all of the constructors who oversaw the development of Britain's ironclad fleet began their careers as apprentices to an experienced shipwright or draughtsman. Reed and White were lucky enough to receive some theoretical training, but the typical career path for a successful member of the Royal Corps of Naval Constructors was an entirely practical one – from Apprentice to Draughtsman Third Class, then Draughtsman Second Class, next Constructor, and finally for a few the pinnacle of the profession – Chief Constructor. This was almost a closed guild, in which knowledge and experience about the mysterious relationships between hull shape, stability, speed, and so forth, were secrets of the trade, passed on from father to son. British warship designers knew as well as their French colleagues that changing the shape of a hull had a rippling effect upon other ship properties, but whereas the calculations, re-calculations and *predictions* of the Poly's graduates relied heavily on quantitative physical theory, the British body of design knowledge depended to a much larger degree on the *inductive* experience of trial-and-error. This was satisfactory in an era of slow and evolutionary change, but centuries of empirical knowledge about the proper distribution of weight on – relatively small – wooden vessels gave few clues to the safe construction of the new iron and steel behemoths.[88]

In the end, of course, French ingenuity and technical prowess could not compensate for Britain's vastly superior industrial potential and, for that matter, Britain's ability to dedicate much greater financial resources to the Great Race at sea. This became especially so after 1870, when the rise of German power forced France to radically change its military priorities and place a policy of 'army first' firmly ahead of the old rivalry at sea. The time had come, declared the *Ministre de la Marine* in 1872, for the Navy 'to sacrifice itself on the altar of the nation'. Its budget was cut by 25 per cent and fleet numbers were sliced from 439 to 137.[89] Yet, even before the disaster of 1870, sceptics had begun to question whether France had committed its scientific and engineering ingenuity to the right kind of navy. The hope had been that, by being the first to transform power at sea from wood and sail, to iron and steam, France could neutralise Britain's numerical superiority in legacy ships and, thanks to steam, overcome its rival's traditional advantage in experienced seafaring personnel. Yet, it was clear that this solution could only have worked if the British had not followed suit – an improbable event under any circumstances. Once they did and committed their vastly more developed iron and ship-building industries to, first catch up and then overtake, the 'Marine Nouvelle,' the French found that the balance at sea had tilted even further against them than had been before *La Gloire* was launched. What France really needed, wrote Admiral Grivil 1869, was not a fleet to fight Britain where it was strongest, but where it was *weakest*. Britain's key vulnerability, he wrote, was its ever-growing dependence on overseas shipping. France's ironclads were fine for fighting against weaker opponents, but against stronger enemies, such as Britain, commerce raiders were the weapons of choice.[90]

Grivil's call for what today would be called an asymmetric strategy, laid the foundation for the *Jeune École* which dominated French naval thought for the next two decades. Spearheaded by Vice Admiral Theophile Aube, the 'Young Schoolers' rejected the preoccupation of mainstream naval thinking with offensive battle squadrons. France's first priority, they said, was defence of the homeland against foreign attack and occupation. While the army naturally carried the main burden, the Navy's primary mission must be *defensive* and to protect the coast against blockade. Its secondary - *offensive* – role would not be to seek out the enemy's battlefleet, but his commercial shipping. The first task would be carried out by flotillas of small, fast torpedo boats, while the second would be the work of unarmoured or lightly armoured cruisers.

Adherents of this view marshalled a host of strategic, technological and economic reasons why this was France's strategy of choice. The strategic rationale has already been mentioned – politically, militarily and financially, it no longer made sense for France to try and match Britain's naval prowess on symmetric terms. In any case, science and technology were about to make the ironclad obsolete. In 1866, the Englishman Robert Whitehead perfected the invention of an Austrian naval officer, by creating the first true self-propelled torpedo. He opened a torpedo factory four years later and, by 1881, torpedoes were exported to a dozen or so different countries. To the *Jeune École*, the torpedo represented, 'the signal precursor of a new era and the first step on a new road which, thanks to the application of science, would revolutionize naval materièl and weapons, and ultimately, a complete revolution in the purpose of navies: naval warfare.'[91] Between the inability of the ironclad to defend itself against the new underwater weapon, and the speed with which it could be delivered, *Jeune École* enthusiasts were convinced they were about to relegate the traditional arbiter of command of the sea – the large gunship – to the dustbin.[92] Swarms of *torpilleurs*, manned by crews bent on attacking *à l'outrance,* would quickly overwhelm the few lumbering behemoths whose commanding officers had overcome the fear of losing their expensive high value units and had dared to venture within reach of the hornets' nests.

Comparative costs seemed to clinch the *Jeune École's* argument: a single ironclad cost 30 million francs, whereas the same amount would buy as many as 14 *torpilleurs* or three commerce-raiding cruisers. If victory at sea inevitably went to the strongest, that is to say, most numerous ironclad fleet, and given that France could not afford to out-build Britain, it was clear that following the British 'model' of sea warfare could only produce an arms race which would not change the balance one iota. The only competition at sea France could conceivably win, was one it could afford (which meant building lots of cheap vessels), and which it would fight on terms not dictated by the opponent's conception of sea power.

Aube received the opportunity to put his theories into practice, when he was put in charge of the *Ministère de la Marine* on January 7, 1886. He held office for only 16 months. This may not seem long, but given that his eight predecessors had averaged eight months, this was quite an achievement in the politics of the Third Republic! Aube reorganised the ministry and slowed down the construction of heavy ironclads in favour of other combatants, including 14 cruisers and 34 *torpilleurs*. Most important for the future was his decision to order France's – and the world's – first '*torpilleur sous-marin électrique*' – the *Gymnote*, a 30-ton submarine, powered by electric batteries and equipped with the world's first practical naval periscope and first naval electric gyrocompass. Because the diminutive craft had a very limited radius of operations and proved unstable while submerged, it was used mainly for experimental purposes. In that role, it made history of a sort in 1890, when it twice successfully broke through a 'blue' blockading fleet. The event contributed to the Royal Navy's decision to abandon its traditional strategy of close blockade.

Aube left office in May 1887; he was succeeded by a textile manufacturer. His departure effectively ended the *Jeune École's* ambitious vision of the Navy's future. The admiral's extensive program of experimental exercises was ended, the scheme to protect ports and harbours with 'mobile defences' of *torpilleurs* halted, and 'counter-revolutionaries,' caught up in the late nineteenth century's 'golden age of navalism,' again sang the praises of heavy ironclads and decisive naval battles. In the end though, and despite inflated expectations about what barely seaworthy craft could accomplish against a blue water fleet, the *Jeune École's* revolutionary vision came much closer to reality than that of the previous generation of ironclad revolutionaries. The battlefleets of the great powers went to war in the summer of 1914 with the lineal descendants of *La Gloire* and *Warrior.* Thirty-four pre-dreadnoughts, dreadnoughts and battlecruisers were lost during the conflict, only four of which as the result of gunfire by their likes. Most fell victim to the new asymmetric weapons such as mines and torpedoes. Only once, at Jutland in 1916, did the big ships fight the kind of mass engagement for which they had been built. Ironically, the commander of the British Grand Fleet, Admiral Sir John Jellicoe, decided not to pursue his enemy, not for fear of his opponent's guns, but the risk of falling into a submarine trap.

Jellicoe's anxiety was symptomatic, of course, of the *real* revolution in naval affairs which had taken place. While the opposing dreadnoughts watched and waited on opposite sides of the North Sea, hoping that the other side would make a mistake and allowed itself to be caught and annihilated piecemeal, the real war at sea was being fought by weapons and with results no one had planned for and few had foreseen. On the German side, the U-boat successors of the *Gymnote* put into devastating practice much of the *Jeune École's* vision of war against the enemy's vulnerable trade arteries.

On the British side, the descendents of the Great Race proved all but useless against the underwater enemy. In fact, the big ships were barred from venturing into the North Sea with the result that they utterly failed in the job they had been designed for and secure command of the waters that mattered most. Instead, just as strategic circumstances forced the Germans to innovate and rely on the U-boat to try and bring the war to a successful conclusion, so the British were compelled to adapt and invent a totally different fleet of sloops, minesweepers, trawlers and decoy ships. After the war, the battleship admirals bravely defended the big ships' role; it was only thanks to the protection of the High Sea Fleet's big guns, they claimed, that the U-boats had managed to survive and inflict their depredations for so long. Confident that the challenge of the submarine had been met and defeated, naval planners in Britain and elsewhere during the inter-war years returned their attention to business as usual. A handful thought that the newly invented airplane might upset the old sea power equation, but the weight of professional opinion stuck to its guns - in this case battleship guns: battleships were too well protected to be sunk by a few, poorly aimed miniscule bombs.

Race into a Cul-de-Sac

The Great Race at sea marks a number of firsts in the history of revolutionary military change. This was the first time that contemporaries were conscious of the fact that they were living in a period of rapid and continuing military change. Dramatic military technological changes had occurred before, but until the industrial-level organisation of science and technology that marked the Industrial Revolution and its military offspring, such change had been slow and extremely gradual.

A closely related consequence was the disappearance of technological continuity in naval affairs. This made planning for and predicting the conduct of future wars at sea far less certain than had been in the past. Naval planners could no longer expect tomorrow's enemy fleet to fight with ships and weapons that were not only almost exact replicas of their own, but which also had changed little, if at all, since the last war. In centuries past, belligerents had usually been as familiar with the quality and shortcomings of the opponent's *materièl* as their own. It was helpful in this regard that captured enemy ships were commonly re-commissioned into one's own fleet.[93] Now, planners had to worry that an opponent might spring a war-winning surprise with unknown new-and-improved guns, better armour arrangements, or devious weapons, such as torpedoes or mines. Ironically, making matters worse was that the new iron and steel ships were much more vulnerable to catastrophic damage by gunfire than their wooden predecessors had been. Namely, for all the guns it carried, the sailing ship of war had been a defensive platform first and an offensive system secondly. Firing at point blank ranges of some 200-300 yards, its 32-pdr guns could penetrate the planking and framing of most ships, but it took a lot of hits near the waterline to inflict a platform kill.[94] Since this was extremely difficult to accomplish, most gun duels aimed at causing a mobility kill by inflicting heavy damage against spars and rigging, causing many casualties among the ship's complement in the process. Basically then, the naval guns of the pre-Industrial Revolution were *people* killers – not ship killers.[95]

Writing at the close of the nineteenth century, one British naval officer mused whether the revolution in naval gunnery was perhaps 'a matter of regret.'[96] Gone was the era of prize-taking, when the practice of capturing had usually benefited his navy most. Gone too was the prospect of the kind of glorious victory of which Nelson had spoken on the eve of Trafalgar – a victory in which the winner, thanks to many enemy prizes, would leave the field of battle with an even stronger fleet than before. The winner in a future Trafalgar might have to celebrate a Pyrrhic victory! There was even more to regret. Writing at the beginning of the twentieth century, Fred T. Jane spoke approvingly of the accelerating pace at which new-and-improved warships were being introduced into navies. A 'different ideal every year,' he wrote, was a 'blessed thing' that ensured against the 'naval decay' from which fleets normally suffered during prolonged periods of peace.[97] Jane did not mention innovation's negative side: rapid obsolescence. For today's military planner, technological obsolescence is a familiar problem; for his Victorian predecessor, the notion that a ship built today would be all but useless in the line of battle five years later, was revolutionary.

Rapid capital depreciation was only one of the costs of rapid innovation; spiralling procurement expenses were another. From the *Warrior* to the *Magnificent* class battleship of 1895, the unit cost of a major warship almost quadrupled. Ship for ship, the new ironclad fleets were sixteen (!) times more expensive than the last generation of sailing navies.[98] And as more and more eggs were being put into – increasingly expensive – baskets, fleet levels declined steadily. In 1815, the French and British navies owned 134 and 79 ships of the line, respectively; 40 years later, the numbers were still respectable – 80 and 54, respectively. Contrast this with August 1914: the Royal Navy deployed 59 battleships, while its French ally barely managed a total of ten.[99] Even these numbers do not fully reflect the decline in effective strength. The fleets of 1815 and 1855 readily mixed and matched ships that might differ in age by as many as 40 years.[100] By contrast, front-line fighting strength in 1914 only counted the dreadnought types built after 1905. This reduced the British and French naval orders of battle to 34 and four battleships, respectively.

Smaller fleets, greater unit cost and comparatively greater vulnerability to modern gunfire confronted naval planners with a highly unsettling strategic and tactical dilemma: how to fight and win a battle without losing the fleet!

Before the revolution at sea, the slow pace of technological change had allowed for a ship that was only partially completed at the end of one war, to be left on the stocks pending the outbreak of another round of hostilities. The unfinished vessel might sit there for years while the builder waited for further funding.[101] Making the ship ready for combat was a relatively simple matter when armaments and fittings had changed little during the intervening years; the biggest problem was to man the newly commissioned vessel with a trained crew.[102] The very slowness of this system was an important strategic advantage, for it gave the loser in a battle a reserve fleet to fall back on and attempt a come-back. This is one reason why, at sea, the strategic effect of so-called decisive battles had usually been temporary; unlike battles on land, sea battles had rarely been conclusive.[103] Now, however, defeat in the first battle could be, in Admiral Sir John 'Jackie' Fisher's words, 'irretrievable, irreparable, eternal.'[104] With no reserve of ships to draw on, the next battle, Fisher warned, would be a single role of the dice with no chance of recovery for the loser. This, in turn, put a premium on striking first, preferably by surprise, or, as Fisher would have it, 'five minutes before war breaks out.'[105] There was only one problem: no one could guarantee the success of a surprise strike, however well planned. After all, success had to mean more than the destruction of the enemy fleet alone – victory could not come at the price of unacceptable damage. In short, the Victorian naval planner had discovered the same quandary that would face his successor in the nuclear era: where lies the power of destruction when each increment in destructiveness makes that power less usable? Tomas Brassey touched on the dilemma in 1875, when he made this case against building more 'monster' ironclads:

> I would suggest one other argument against building ships of exaggerated size. Will not a captain be burdened with an almost intolerable anxiety, when he knows that his ship is one of a very limited number, and that the loss of such a ship may be a serious blow to the Navy? In the numerous fleets of the olden times, the fate of an individual ship was a less momentous question. But if you concentrate the whole powers of the Navy in a few ships, such as we have lately built, you throw upon the officers in command an intolerable weight of responsibility. You will restrain and chill that gallant and almost

> reckless ardour with which the great battles of the past were fought and won.[106]

When steam, steel and shell-firing guns became available for combination into a single seagoing package, naval planners and warship builders naturally sought to apply the new technologies to the existing and familiar paradigm of power at sea - the line of battle ship. History had shown that when fleet met fleet, the side with the most ships – and therefore the most guns – usually won. The new technologies were basically grafted onto this principle, the assumption being that the new fleets of steam and steel were merely the more powerful successors of their wooden predecessors. It was an assumption that was central to the work of the great navalist writers at the close of the nineteenth century – Mahan, the Colomb brothers, Corbett and others. Each and everyone of the 'pens behind the fleet' took for granted that, while technology might change the shape of fleets, they would still fight according to certain timeless and, to quote Mahan, 'immutable principles.'[107] The reality proved very different: the Great Race produced a weapons system which created its own consequences. From a narrow military point of view, the ironclad and its battleship successor proved largely irrelevant to the purpose they were ostensibly to fill: decisive battle *à la* Trafalgar. Cost, rapid obsolescence, and the fear of losing one's scarce 'baskets' did indeed serve to 'restrain and chill that almost reckless ardour with which the great battles of past were fought and won.' Furthermore, the same technical and industrial skills that fuelled the Great Race spawned a host of cheap and below-the-belt weapons – torpedoes, mines, etc. – which served to overturn the 'immutable principle' that only likes fought likes. Looking back, it is easy to sympathize with the opinion of the man who oversaw the building of *Warrior*, Nathaniel Barnaby. France's decision to build warships protected with iron plating, Barnaby reminisced, had been a mistake, made 'unhappily for England…and unhappily for herself.'[108]

Endnotes

[1] National Archives (formerly Public Record Office), ADM 116/1, 'Confidential Report on Navy Estimates 1852-1858; England and France,' Vol. 1, p. 21.
[2] *Ibid*., p. 13.
[3] *Ibid*., pp. 34-39. Also, S. Eardley-Wilmot, *The Development of Navies During the Last Half-Century*, (London: Seeley and Co., 1892), pp. 43-44.
[4] 'Confidential Report on Navy Estimates 1852-1858; England and France', Vol. 1, Appendix No. 7: 'Reports by Lt. Col. R. Claremont to Earl Cowley', p. 39.
[5] James Phinney Baxter, 3rd, *The Introduction of the Ironclad Warship*, (Cambridge: Harvard University Press, 1933), p. 20.
[6] 'Reports by Lt. Col. R. Claremont to Earl Cowley,' *op. cit*., p. 13.
[7] Andrew Lambert, *Steam, Steel & Shellfire: The Steam Warship 1851-1905*, (London: Conway Maritime Press, 1992), p. 23.
[8] See, David K. Brown, *Before the Ironclad: Development of Ship Design, Propulsion and Armament in the Royal Navy, 1815-1860* (hereafter as *Before the Ironclad*), (London: Conway Maritime Press, 1990), p. 64.
[9] *Ibid*.
[10] *Ibid*., p. 61.
[11] For a description of the difference between side lever and direct-acting engines, see Basil Greenhill and Ann Giffard, *Steam, Politics & Patronage: The Transformation of the Royal Navy 1815-54*, (London: Conway Maritime Press, 1994), pp. 55-57.
[12]*Before the Ironclad*, p. 62. By contrast, it has been estimated that the weight of the propulsion arrangement of a 74-gun ship at the Battle of Trafalgar amounted to about 3.5 per cent of total displacement. Source: Sir Percy Woods, 'The Ships of the Royal Navy as they Existed at the Time of Trafalgar.' Paper read to the Institution of Naval Architects, July 19, 1905. http://www.home.gci.net/~stall/traf.htm.
[13] *Before the Ironclad*, p, 204.
[14] *Naval Development in the Century*, p. 109.
[15] Greenhill and Giffard report that in the early paddlewheelers up to 90 per cent of the engine's potential power was wasted. *Steam, Politics & Patronage*, p. 47.
[16] Bernard Brodie, *Sea Power in the Machine Age*, 2d ed. (Princeton: Princeton University Press, 1943), p. 32.
[17] *Steam, Politics & Patronage*, p. 43.
[18] For the argument that French screwliners were generally superior over their British counterparts, see C.I. Hamilton, *Anglo-French Naval Rivalry 1840-1870*, (Oxford: Clarendon Press, 1993), pp. 54-58
[19] The full title is *Nouvelle force maritime ou exposé des moyens d'annuler la forces des marines actuelles de haut bord et de donner à des navires très petits assez de puissance pour détruire les plus grands vaisseaux de guerre.* Cited in Etienne Taillemite, '*Henri-Joseph*

Paixhans et sa nouvelle force maritime,' p. 2. http://www.stratisc.org/pub/pn/PN4_TAILLEMITE.html. The discussion of Paixhans' ideas is largely drawn from this source.

[20] *Ibid*.

[21] Ian Hogg and John Batchelor, *The Naval Gun*, (Poole: Blandford Press, 1978), p. 25.

[22] One British author wrote, in 1892, how Paixhans' idea, in 1825, that line-of-battle ships might need protection from 7-8 inches of iron, 'indicated an amount of protection which was not reached for some years, as though he had an inkling of the later development of ordnance now so familiar to us.' *The Development of Navies*, pp. 45-46.

[23] *Ibid*., p. 27.

[24] *Introduction of the Ironclad Warship*, p. 26, and *The Naval Gun*, p. 29.

[25] Paixhans was not the only advocate of armoring warships. One other key activist was French naval officer de Montgéry. See, *The Introduction of the Ironclad Warship*, pp. 27-29.

[26] Oscar Parkes, *British Battleships "*Warrior*" 1860 to "*Vanguard*" 1950: A History of Design, Construction and Armament*, (Hamden: Archon Books, 1970), p. 420.

[27] Frederick Leslie Robertson, *The Evolution of Naval Armament*, (London: Constable & Co., 1921), p. 164.

[28] *The Introduction of the Ironclad Warship*, p. 60.

[29] The Arsenal Ship concept envisaged a barge-like floating platform armed with up to 500 Tomahawk-like land attack cruise missiles. Excessive vulnerability (too many eggs in too few baskets) has been cited as the reason the scheme never progressed beyond the conceptual stage.

[30] *Ibid*., p. 92.

[31] H.W. Wilson, *Ironclads in Action*, (London: Sampson Low, Marston and Co., 1898), p. 260.

[32] See, for example, *Steel, Steam & Shellfire*, p. 53. Also James Phinney Baxter, 3rd, p. 113.

[33] Statistics for British and French output of pig iron are taken from B.R. Mitchell, *European Historical Statistics 1750-1970*, abridged ed. (New York: Columbia University Press, 1978), pp. 215, 216.

[34] Louis Figuer, *Les Merveilles de la Science*, (Paris: Librairie Frune, 1870), pp. 528-29.

[35] *The Introduction of the Ironclad Warship*, p. 115.

[36] Cited in Louis Figuier, p, 529. Translated into English, Dupuy de Lôme promised that if only one of his new warships were launched into the midst of a fleet made entirely of wood, it and its 36 cannons would be like a lion among a herd of sheep.

[37] *Ibid*., p. 123.

[38] Cited in Parkes, *British Battleships,* p. 11,

[39] *Sea Power in the Machine Age*, p. 3.

[40] This argument has been made most cogently by Hamilton in his *Anglo-French Naval Rivalry*, especially pp. 272-74.

[41] *Ibid*., p. 274. My emphasis.

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[42] H.W. Wilson, *Ironclads in Action: A Sketch of Naval Warfare from 1855 to 1895*, (London: Sampson Low, Marston and Co., 1989), p. 209.

[43] For example, the English armies did not give up their longbows in favor of exclusive reliance on firearms until the middle of the seventeenth century. As late as 1798, there were still those in England who urged the retention of the bow as a national weapon in combination with, of all things, the pike. David Eltis, *The Military Revolution in Sixteenth-Century Europe*, (New York: Barnes & Noble Books, 1995), p. 102.

[44] Marin Hanri Jansen, *De omwenteling in het zeewesen: eene bijdrage tot het behoud van de onafhankelijkheid*, (Dordrecht: Braat, 1864). The book was translated into English with the title, *The Revolution in Naval Affairs*, (London, 1876).

[45] Sir Howard Douglas, *On Naval Warfare with Steam*, (London, 1858). Cited in Jeremy Black, *War and the World: Military Power and the Fate of Continents 1450-2000*, (New Haven: Yale University Press, 1998), p. 166.

[46]For a discussion of technological change during the last decades of the sailing ship-of-the-line, see Brian Lavery, *The Ship of the Line, Vol. I: The Development of the Battlefleet 1650-1850*, (Annapolis: Naval Institute Press, 1983), pp. 130-54.

[47] *Naval Development in the Century*, pp. 23-24.

[48] *Ibid*., p. 11.

[49] Warships in Ordinary were those that were deemed a temporary surplus to current requirements. Moored to buoys, they carried no masts and guns and were manned by a handful of officers, a purser and a cook. See, Nicholas Blake and Richard Lawrence, *The Illustrated Companion to Nelson's Navy*, (Mechanicsburg: Stackpole books, 2005), p. 12.

[50] Governments did used spies and informants during war. For example, the Royal Navy used spies during the Napoleonic wars to gather intelligence about the preparations and movements of the French fleet, but these activities ceased when the fighting was over. See, Thomas G. Fergusson, *British Intelligence, 1870-1914: The Development of a Modern Intelligence Organisation*, (London: Arms and Armour Press, 1984), p. 8.

[51] Philip Sims, 'Trends in Surface Warship Design 1861-1983', Naval Engineers Journal, May 1983, p. 34.

[52] The most dramatic instance is the fate that befell the British battleship *Captain*, a fully rigged turret ship. Her displacement had been estimated at 6,963 tons, but she was delivered at 7,767 tons. As a result the design freeboard of eight feet was reduced to six. On her maiden voyage and caught in a storm in September 1870, she capsized with the loss of most of her crew, as well as her designer, Captain Coles.

[53] Some French commentators thought that the decision to leave part of *Warrior*'s hull unprotected indicated that the British had to yet make up their minds whether the wooden walls were truly gone. *Ibid*., pp. 548-49.

[54] The French navy rejected the covered turret because of ventilation problems. See, Siegfried Breyer, *Battleships and Battle Cruisers 1905-1970*, 9London: Macdonald and Jane's 1973), p. 29.

[55] Parkes, *British Battleships* new and revised ed. (Annapolis: Naval Institute Press, 1990), p. 230. The book was originally published in 1957,with a second edition appearing in 1966.

[56] Even as late as 1882, Sir Thomas Brassey, a member of the British Parliament and a prolific naval commentator, observed that, 'The practice with naval guns in action at distances exceeding 1,000 yards will be so uncertain that it is not necessary to consider the penetrative power of guns beyond that limit. It is indeed more than probable that the effective fire of guns will be delivered within rather beyond a range of 500 yards.' Sir Thomas Brassey, *The British Navy: Its Strength, Resources, and Administration*, Vol. III, (London: Longmans, Green and Co., 1882), p. 29.

[57] Archibald S. Hurd, *Naval Efficiency: The War-Readiness of the Fleet*, (London: Chapman & Hall, 1902), p. 11.

[58] Cited in John Beeler, *The Birth of the Battleship: British Capital Ship Design 1870-1881*, (Annapolis: Naval Institute Press, 2001), p. 87.

[59] *British Battleships*, pp. 252-55.

[60] Vice-Admiral P.H. Colomb, *Memoirs of Admiral The Right Honorable Sir Astley Cooper Key*, (London: Methuen & Co., 1898), p. 325.

[61] *Ibid*, p. 335.

[62] *Ibid*., p. 224.

[63]Sir Edward J. Reed and Edward Simpson, *Modern Ships of War*, (New York: Harper & Brothers, 1888), p. 53.

[64] Colomb, *op. cit*., p. 340.

[65]Sir Thomas Brassey, *British Navy: Its Strength, Resources, and Administration, Vol. III, Part III: Opinions on the Shipbuilding Policy of the Navy*, (London: Longmans, Green, and Co., 1882), p. 207.

[66] *Ibid*., p. 21.

[67]M. Marshal, '*Les Navires de Combat les Plus Récents*', *Revue Maritime et Coloniale* (Paris), February 1876, p. 373.

[68] P. Dislère, '*La Marine Cuirassée – Résumé – Conclusions'*, *Revue Maritime et Coloniale* (Paris), August 1873, p. 517.

[69]*Ibid*., p. 522.

[70] *Report of the Committee on Designs for Ships of War*, July 26, 1871. Cited in Brassey, *op. cit*., p. 521.

[71] *Ibid*., p. 522,

[72] *Ibid*., p. 523.

[73] The output of French crude steel in 1875 was 239,000 metric tons, compared with 719,000 tons in Britain. *European Historical Statistics 1750-1970*, p. 223.

[74] *Birth of the Battleship*, p. 38.

[75] For a summary of the development of naval armor up to World War I, see Edward L. Attwood, *The Modern Warship*, (Cambridge: Cambridge University Press, 1913), pp. 27-32.

[76] *Birth of the Battleship*, pp. 96-97. According to Ropp, the French had been conducting tests with steel shells since the early 1870s, whereas the British waited until 1884. *The Development of a Modern Navy*, p. 66.

[77] David S. Landes, *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present*, (Cambridge: Cambridge University Press, 1969), p. 260.

[78] When Bessemer invented his converter technique, he had by mere chance used a very pure iron ore. However, when low grade ores were used, the system was unable to burn off the acid phosphorus and other impurities. Anything more than minute proportions of these elements made the steel unworkable. On the pros and cons of different steel-making processes, see *The Unbound Prometheus*, pp. 249-69.

[79] *Naval Development in the Century*, pp. 51-59.

[80] *Ibid*., pp. 33, 45.

[81] The cap was a soft-steel jacket covering the shell's hardened point so as to absorb the force of impact and pre-stress the armor before breaking it aside and allowing the main shell to do its work.

[82] Until 1904, the British navy's premier gunnery exercise, the Annual Prize Firings, were held at 1,400-1,600 yards. In 1905, the Battle Practice was introduced, which had ships shoot at stationary targets at ranges from 5,000 to 7,000 yards. See, Peter Padfield, *Aim Straight: A Biography of Sir Percy Scott, the Father of Modern Naval Gunnery*, (London: Hodder and Stoughton, 1966), p. 150. See also, Jon Tetsuro Sumida, *In Defence of Naval Supremacy: Finance, Technology and British Naval Policy 1889-1914*, (London: Unwin Hyman, 1989), pp 71-76.

[83] The atrocious accuracy of late nineteenth century naval gunfire was demonstrated dramatically in the Spanish-American War. In the Battle of Manilla in May 1898, only 142 out of 5,895 shells fired by the American ships at virtually point blank range, hit their Spanish targets for a hit rate of 2.5 per cent. Two months later, at Santiago Bay in Cuba, 8,000 rounds were fired at stationary targets between one-half and three miles away. One hundred and twenty-nine hits were scored for a hit rate of 1.5 per cent. See, Padfield, *op. cit*., p. 85, 87-88.

[84] It was not until 1892 that the British Admiralty set a requirement for a rangefinder accurate to 3 per cent at 3,000 yards. See, 'The British Optical Munitions Industry before the Great War', http://www.ehs.org.uk/ehs/conference 2004/assets/sambrook.doc. Not long after, the Royal Navy's Mediterranean Fleet attempted long-range gunnery practice at 6,000 yards, but this did not become a fleetwide practice until 1905. See, John Brooks, *Dreadnought Gunnery and the Battle of Jutland: The Question of Fire Control*, (London: Routledge, 2005), p. 40.

[85] *Ibid*., p. 116.

[86] This difference also explains France's initial lead in high quality steel. French steel makers were able to achieve and maintain steel of good, uniform quality thanks to the early establishment of an excellent system of metallurgical schools. Their British counterparts, by contrast, 'tinkered and improvised," with the result that, "the irregularity of their product merely

confirmed the doubts of consumers, which in turn discouraged experiment and investment.' See, *The Unbound Prometheus*, p. 263.

[87] For a contemporary American account of the curriculum at the *École Polytechnique*, see Philip Highborn, *Report on European Dock-Yards*, (Washington, DC: Government Printing Office (GPO), 1886), p. 80.

[88] It is interesting to speculate whether the slow technical evolution of the warship during the centuries prior to the 'Great Race' can be attributed, in part, to the 'craft-like' nature of ship design process.

[89] Cited in Rolf Hobson, *Imperialism at Sea: Strategic Thought, the Ideology of Sea Power, and the Tirpitz Plan*, (Boston: Brill Academic Publishers, 2002), p. 97.

[90] Louis Antoine Richild Grivil, *De la guerre maritime avant et depuis les inventions* (Paris 1869). Cited in Hobson, *op. cit.*, p. 97. See also, Étienne Taillemite, '*Un théoricien méconnu de la guerre maritime: l'amiral Richil Grivel*', Hervé Couteau-Begarie, Ed., *l'Évolution de la pensée navale*, Vol. II, (Paris: Economica, 1990-1997), http://www.stratisc.org/PN2_TAILLEMITE.html.

[91] Pene Siefert, *La Marine en danger*. Cited in Capitaine de Frégatte Ceillier, '*Les idées stratégiques en France de 1870 à 1940: La Jeune École*', (1928) reproduced in *l'Évolution de la pensée navale*, Vol. I, http: www.stratisc.org/PN1-CEILLIERJE.HTML.

[92] Early torpedo boats (*torpilleurs* in French) were 100 to 150 feet long, had a speed of 20-30 knots, and carried three torpedoes. The *torpilleur* evolved into the modern day destroyer.

[93] More than 200 captured enemy ships were re-commissioned into the Royal Navy during the French Revolutionary and Napoleonic wars. Far fewer British ships joined the French fleet, in part, because the French were less successful at sea, but also because, just as the British preferred French (and Spanish) made warships over their own, so the French cared little for British-built ships. The latter tended to be slower sailers, carried smaller and less efficient guns at less height, were usually older, and tended to pitch more violently in a seaway. On British captures, see Otto von Privka, *Navies of the Napoleonic Era*, (London: Newton Abbot, 1980), pp. 221-38.

[94] An astonishing illustration of the toughness of the sailing warship is the French *Guillaume Tell*. This 80-gun vessel fell in with the British 74-gun *Foudroyant*, the 64-gun *Lion* and the frigate *Penelope* off Malta in March 1800. The French vessel struck her colors after a fight that lasted two hours and 20 minutes, in which *Foudroyant* alone expended over 2,700 32-pd, 24-pd, and 12-pd, shots. Though heavily damaged, the French ship was repaired and re-commissioned into the British fleet as the *Malta*. See, J. Scoffern, *Projectile Weapons of War and Explosive Compounds*, (London: Longman, Brown, Green, and Longmans, 1858), pp. 154-55. The main reasons for the sailing warship's limited ship-killing potential were low muzzle velocities (and therefore poor striking power), excessive so-called 'windage' (the space between the cannonball and the gun barrel), and poor accuracy.

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[95] Not one Franco-Spanish ship in the Battle of Trafalgar was sunk by enemy gunfire, but the dead and wounded numbered 2,600 for an average of about 80 for each vessel in the 33-ship strong allied fleet. The British average was 60.

[96] Captain S. Eardly-Willmott, *The Development of Navies During the Last Half-Century*, (London: Seeley and Co., 1892), p. 61.

[97] Fred T. Jane, *Heresies of Sea Power*, (London: Longmans, green and Co, 1906), pp. 294-95. Jane became the founder of the 'bible' of navalists, *Jane's Fighting Ships*.

[98] A 1,700-ton 74-gun sailing warship built in the early 1820s cost about £60,500. See, Andrew Lambert, *The Last Sailing Battlefleet: Maintaining Naval Mastery 1850-1850*, (London: Conway Maritime Press, 1991), p. 125.

[99] Date derived from George Modelski and William R. Thompson, *Seapower in Global Politics, 1494-1993*, (Seattle: University of Washington Press, 1988), pp. 76, 77, 227, 229, 264, 265.

[100] Nelson's HMS *Victory* was launched in 1765, commissioned in 1778, and continued in active service for the next 32 years.

[101] Few ships remained on the stocks as long as the nine 74-gun ships of the line authorized by the U.S. Congress in 1816. The first two, *Delaware* and *North Carolina*, were laid down in 1817 and launched in 1820. The next four were laid down in 1818, with the first one, *Vermont*, launched in 1845. The second, *New York*, was still on the stocks, when she burnt in 1861; *Alabama* was launched in 1864, and *Virginia* was finally broken up on the stocks in 1864 – 57 years after the keel had been laid. Harold and Margaret Sprout, *The Rise of American Naval Power, 1776-1918*, (Princeton: Princeton University Press, 1944), pp. 88-89, and Stephen Howarth*, To Shining Sea: A History of the United States Navy, 1775-1991*, (New York: Random House, 1991), p. 129.

[102] According to Sir Henry Briggs, who was the British Admiralty's chief clerk from 1827 to 1892, it took during the 1830s from three to six months to collect a crew for a large frigate or line of battleship, and another six months to bring order and discipline. See his *Naval Administrations 1827-1892*, (London: Sampson Low, Marston & Co., 1897), p. 58.

[103] For a more extensive discussion of why decisive naval battles are a historical rarity, see my 'The Burden of Trafalgar: Decisive Battle and Naval Strategic Thinking on the Eve of World War I', Geoffrey Till, Ed., *Sea Power: Theory and Practice*, (London: Frank C. Cass, 1994), pp. 35-151.

[104] Admiral of the Fleet Lord Fisher*, Records*, (London: Hodder & Stoughton, 1919), pp. 94-95. Fisher made the remark in 1890.

[105] *Ibid*., pp. 90-92.

[106] Sir Thomas Brassey, *The British Navy: Its Strength, Resources, and Administration*, Vol. III, (London: Longmans, Green, and Co., 1882), p. 203.

[107] The term 'pens-behind-the fleet' is borrowed from the title of Chapter V in W. Mark Hamilton, *The Navy and the Nation: Methods and Organization of British Naval Propaganda, 1889-1924*, (New York: Garland Publishers, 1986), p. 176.

108 Nathaniel Barnaby, *Naval Development in the Century*, (Toronto: The Linscott Publishing Co., 1904), p. 62.

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