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CHAPTER FOUR

Fish and Ships: Models in the Age of Reason

Simon Schaffer

> Emerson has no patience with analysis. A Ship to him is the Paradigm of the Universe. All the possible forces in play are represented each by its representative sheets, stays, braces, and shrouds and such—a set of lines in space, each at its particular angle. Easy to see why sea-captains go crazy—godlike power over realities so simplified (Pynchon 1997, 220).

This chapter is concerned with models of electric fish and of ships' hulls made in late eighteenth-century London to manifest rational principles in the artificial and the natural realms. The two stories told here relate to the establishment of new sciences in the decades around 1800. Models of electric fish were decisive in the construction of the electric pile, so helped spawn newfangled chemical physiology and electrodynamics. Elegant trials with ship models showed how rational mechanics could join a new alliance of military and academic sciences. Furthermore, both projects were entangled with important philosophical puzzles, newly pressing in the wake of the work of David Hume. One problem involved the possibility of inferring prescriptions from descriptions, another challenged the legitimacy of projecting from microscopic to macroscopic systems. Solutions to the scale problem—the puzzle of generalising from intimately manageable trials to full-size realities—might establish model-builders' own rights and skills. It was important to navigate between an overambitious claim that natural philosophy could simply govern commercial schemes and the worrying charge that natural philosophers were incompetent to judge the worlds of trade and industry. There was thus a politics implicated in modelling. Mimicry of artificial or natural systems often involved remodelling the social order of production and design. The chapter traces ways in which these imitative and normative structures allowed moves between the making of representations and the exercise of power.

The novelist Thomas Pynchon's recent fictionalised image of the eighteenth-century mathematician William Emerson rings true more generally. Ingenious simplification seemed then to offer "godlike power over realities". Enlightened measures required manageable spaces where otherwise unruly phenomena could be directed at will by expert reason often backed with force (Lindqvist 1990; Edney 1994; Alder 1997, 56–86). In Britain, such spaces included those run by industrial managers and the state, patrons of metropolitan trades in instrument design and modelling (Ogborn 1998, 194–98; Ashworth 1998b; Millburn 1988). Inside these institutions and on the public stages they sponsored, modelling might capture the artificial world of mechanics and the natural economy of creation. Mechanics knew these worlds were not orderly systems well mimicked by wood and string, but modelling made them seem so or suggested how they might become so. Warships were not designed by slavish imitation of principles of rational geometry and enlightened mechanics. Yet trying ship models showed how shipwrights might change their ways and become subservient to reason. So in the natural order too, the enlightened natural philosophy which saw electric action in lightning storms and stingrays got its authority from building viable models, then argued for lightning-rods or the truths of galvanism. When model-makers designed, tried, and showed their well-behaved models, they could claim the right to govern and represent the macroscopic systems these models represented.

British engineers of the period were keen on trial models, in contrast with French mathematical analysis or American exploratory projects (Smith 1977; Kranakis 1997). Test models were favoured by enlightened instrument-makers turned civil engineers, such as James Watt and John Smeaton. In the 1760s the entrepreneurial Watt conducted repairs at Glasgow University to "a workable model of a Steam Engine which was out of order". Such models were crucial for his engine trials, in the law suits which plagued Watt's patent claims, and in his industrial plans for rational maximisation of profit and discipline (Hills 1989, 51–54; Robinson and McKie 1969, 254, 364; Miller 2000, 5–7). Smeaton was equally entrepreneurial, ambitious for philosophical status, and legally embroiled. He used small-scale experimental machines to estimate the friction and efficiency of his great mill wheels, and applied the same model technique in 1762 for experiments run on a

London fishpond by the newly formed Society of Arts to assess the best design for ship hulls (Reynolds 1979; Smith 1973–74, 181, 184; Robinson and McKie 1969, 429; Harley 1991). Watt showed the originality of his steam-engine designs, Smeaton proved overshot water-wheels were more efficient, and the Society of Arts demonstrated the speed of conventional ships, using models which made natural principles manifest and their own skills authoritative (Morton 1993; Stewart 1998, 275–76; Miller 1999, 188–91). The establishment of such authority was not easy. In the 1770s, the Cambridge mathematician George Atwood commissioned a pulley machine, which by minimising friction could show the truth of Cambridge mechanics. Atwood used this demonstration model to evince the fallacies of modish ideas about self-moving matter, espoused by republican agitators such as Joseph Priestley and later Tom Paine. Atwood's loyalty was rewarded with a lucrative government job when his student, William Pitt, became prime minister in 1784. Atwood also reckoned that models like those of Smeaton should never be used to challenge the academic truths of Newtonian mechanics. The omnipresence of friction in real world mills would frustrate any inferences from their working to the cloistered principles of established natural philosophy (Schaffer 1994, 173–74).

Since mechanical reasoning was supposedly governed by scale-insensitive geometry, it seemed hard to understand why projection to larger systems ever failed. The Wearside mathematician William Emerson, Pynchon's exemplary protagonist, treated this scale problem in a best-selling mechanics textbook (1758), which reached a fourth edition by 1794 (Hamilton 1952). Emerson referred his readers to the origin of classical mechanics, Galileo's *Two New Sciences* (1638). Galileo had used the scale puzzle as the basis of his new science of the strength of materials, formulating principles of levers, pulleys, and beams which would explain the role played by materials' own weight in large-scale structures (Galileo 1974, 11–14). These problems of reasoning from scale models in new materials still haunted engineering in the late eighteenth century (Skempton and Johnson 1962). In 1798, inspired by the success of iron bridges in the Midlands and the North, plans were launched for a vast iron bridge across the Thames to allow larger ships into the crowded wartime London docks. Parliament set up a committee to investigate the plan. Atwood and Watt were members, as was the Royal Military School professor Charles Hutton. The engineer Thomas Telford constructed a model of an iron bridge spanning 600 feet for show at the Royal Academy and before the Committee (Skempton 1980). Atwood commissioned his own experimental model arch (Fig. 4.1), then derived numerical data to guide unprincipled engineers. This model of brass and wood convinced him his Newtonian mechanics could explain all the properties of complex stone and iron arches. He claimed engineers had struck on satisfactory designs by luck. Their "fortuitous arrangements" were helped by friction, a force aiding cohesion of the most rickety and untheorised structures. So models and rational mechanics demonstrated that "practical artists" had always followed "rules established by custom, without being referred to any certain principle" (Atwood 1801, vi–vii and supplement, vii–viii).

In these enterprises of 1790s engineers and analysts, the rival claims of custom and principle were fought out with experimental models. Some showed that artisan custom was a legitimate authority; others that rational principles could govern mere tradition. Hutton, for example, considered that Atwood's trials on bridge models, "though common and well-known to other writers, he unfortunately fancied to be new discoveries". The conservative philosopher Samuel Taylor Coleridge saw Atwood's bridge model on show at Kew Observatory. Reflecting on enlightenment's failings, Coleridge used the apparent weakness of the mathematician's elegant set-up to suggest the fallacies of rationalist analysis and to laud custom and inspiration (Hutton 1815, 1: 189–90; Coleridge 1956–59, 4: 588; Coleridge 1969, 496–97). These contrasts between customary conduct and rational principles were the stuff of antagonistic politics and philosophy, especially in the wake of Edmund Burke's *Reflections on the Revolution in France* (1791). Burke damned the revolutionaries as deluded utopians whose model societies violated custom and would fail in practice (Golinski 1992, 178). Those who countered Burke often appealed to the rationality of mechanical models. Immanuel Kant's 1793 essay on theory and practice argued against Burke that enlightened reason could indeed be applied to mundane affairs. Kant offered a critique of the Burkean account of "the British constitution, of which the people are so proud that they hold it up as a model for the whole world" (Kant 1991, 83). He used rational mechanics to show that the apparent feebleness of high theory was a consequence of incomplete theoretical work:

> All of us would ridicule the empirical engineer who criticised general mechanics or the artilleryman who criticised the mathematical theory of ballistics by declaring that while the theory is ingeniously conceived, it is not valid in practice, since experience in applying it gives results quite different

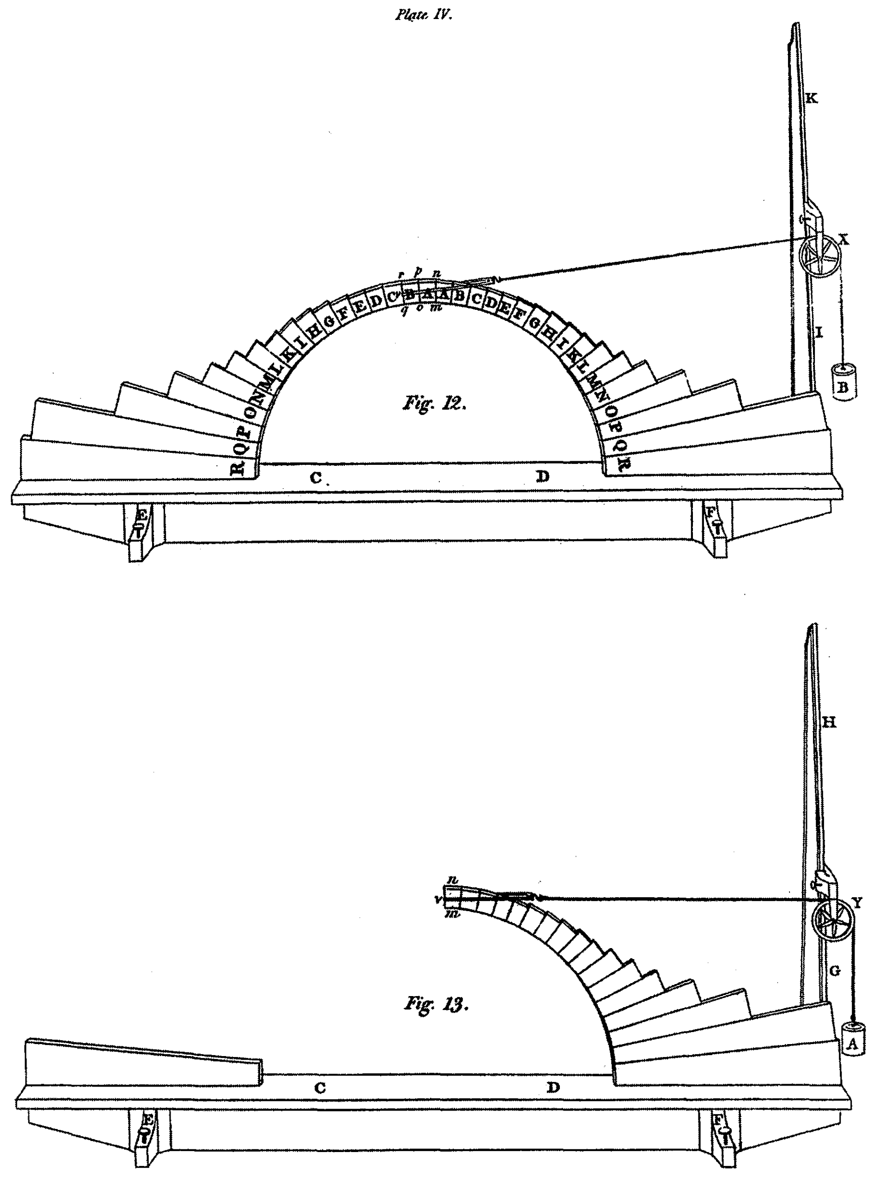

Figure 4.1 George Atwood's experimental model of the load-bearing capacity of London Bridge, built in 1803 by Matthew Berge. Atwood used balance weights held over the pulley to estimate the forces at work in different arch designs. Samuel Taylor Coleridge saw this model at Kew Observatory in 1811. Source: George Atwood, *Dissertation on the Construction and Properties of Arches*, supplement (London, 1804), pl. 4. By permission of the Syndics of Cambridge University Library.

> from those predicted theoretically. For if mechanics were supplemented by the theory of friction and ballistics by the theory of air resistance, in other words if only more theory were added, these theoretical disciplines would harmonise quite well with practice (Kant 1991, 62).

"If only more theory were added"—the slogan of enlightened reason. Tom Paine's *Rights of Man* (1791) was the most radical answer to Burke. Paine called his pamphlet "my *political* bridge". He linked his development of better models of political order with his long-term work in bridge design (Keane 1995, 282). From the mid-1780s Paine sought backing for a novel iron bridge, first in Pennsylvania, then across the Thames, the Seine, or even the English Channel. He made spectacular demonstration models for his friend Benjamin Franklin, then brought them to Paris and London in 1787. Paine claimed his designs were fundamentally *natural* models, based on the laws of spiders' webs. He toured Midlands ironworks with Burke, met academic engineers in Paris, sought support from the Royal Society's president Joseph Banks and persuaded the Ordnance Board's gunfounders to build a huge model bridge in London for public show. The scheme failed. Patrons were more impressed by Telford's models than those of Paine (Kemp 1977–78; James 1987–88; Keane 1995, 267–82). But when he composed his *Age of Reason* in a Paris jail in 1793, Paine used mechanical models as the basis of his incendiary assault on the "stupid Bible of the Church". God became "the great mechanic of the creation" whose cult was embodied in models such as orreries, which Paine had seen with enthusiasm in London in the late 1750s. "We know that the greatest works can be represented in model", Paine argued, "and that the universe can be represented by the same means . . . The same properties of a triangle that will demonstrate upon paper the course of a ship will do it on the ocean" (Keane 1995, 42; Paine 1991, 73–76, 82, 188–89). This 'age of reason' involved the rational application to the cosmos and polity of allegedly natural principles first demonstrated in mechanical models.

FISH

For the London showmen who had so attracted Paine, electricity was a pre-eminent natural power. The aesthetics of electricity corresponded to those theorised by Burke in his *Philosophical Enquiry* on the sublime and the beautiful (1757). Models could show how sublime phenomena might be

managed in the macrocosm. The invention of the Leyden jar in the mid-1740s, Benjamin Franklin's account of its operation, and his arguments for the possibility of protecting against the terrors of lightning with tall, pointed, well-grounded metal rods reinforced electrical modelling (Cohen 1990, 142). Franklin hung a pair of brass scales, one pan of which was electrified, from a wooden beam. This mimicked thunder clouds. Twist the balance so that its pans would slowly spin and descend. If hung over some vertical metal instrument, the array would spark violently. But if a pin were attached to the top of the instrument, or one's finger were slowly brought towards the array, the model cloud would slowly discharge without sparking (Franklin 1941, 212–36, 406). In early 1753 at St Johns, Antigua, a capital of the West Indian sugar plantocracy, one of Franklin's allies demonstrated how an electrical flash could be "made to strike a small house and dart towards a little lady sitting upon a chair, who will, notwithstanding, be preserved from being hurt; whilst the image of a negro standing by and seeming to be further out of danger will be remarkably affected by it". Thunder houses, electric models of churches, and of powder magazines, were also on show (Warner 1997). A London draper, William Henly, backer of Franklin's theory, performed model trials in spring 1772 using a thunder house "which I thought a nearer resemblance of the operations of nature on these occasions". To counter the worry that clouds move and float, while the prime conductors he used were static, he modelled clouds with a copper-coated bullock's bladder. Other electricians used metal-plated placentas for this trick (Franklin 1959–, 18: 229–31 and 19: 119–21; Henly 1774, 135, 142, 145–46). The ambitious society painter and electrical philosopher Benjamin Wilson contested Franklin's rod recipe. He built his own models to show that points were dangerous because they would pull electricity from any passing cloud (Wilson 1764).

Franklin was in the imperial capital as Pennsylvania's lobbyist and habitué of philosophical and commercial clubland. He explained why models of clouds with cotton rags and metal rods, and the imitation of high buildings by his own finger, should compel his confrères. "It has also been objected that from such electric experiments, nothing certain can be concluded as to the great operations of nature, since it is often seen that experiments which have succeeded in small, in large have failed. It is true that in Mechanics this has sometimes happened. But . . . we owe our first knowledge of the nature and operations of lightning to observations on such small experiments" (Franklin 1959–, 19: 253). This knowledge became politically crucial. Between 1763 and 1768 the Ordnance Board arranged to shift its large powder magazines, whence the navy was supplied, from Greenwich down the Thames to Purfleet. In 1771 the government imposed new safety regulations on the magazines (Hogg 1963, 1: 108–9). In May 1772 both Wilson, hired as the Ordnance Board's artist and a well-supported royal client, and Franklin, the Royal Society's spokesman, advised on lightning-rods at Purfleet. The embarrassing and politicised conflict between Wilson's critique and Franklin's endorsement of high pointed rods forced the appointment of a committee dominated by Franklin's allies, including the aristocratic natural philosopher Henry Cavendish, who in winter 1771–72 presented the Royal Society with an important new paper on exact trials of electric forces (Randolph 1862, 1: 24–25; Heilbron 1979, 379–80; Franklin 1959–, 19: 153–56, 232–33; Cavendish et al. 1773). Debates centred on the right interpretation of the model experiments of Franklin, Henly, and Wilson. Wilson rightly claimed that points could not discharge distant thunderclouds. Franklinists rightly answered that protection was better the higher the conducting rod above the building. The conflict revealed the political fractures of metropolitan life in the epoch of the American war. It also raised important issues for model-makers (Franklin 1959–, 19: 424–30).

In his dissenting report, completed at the end of 1772, Wilson defended small-scale modelling precisely because real-world electrical phenomena were so obscure. He reflected that test models got status because they accurately represented the world, but then this status was used to test the representation's accuracy. Wilson reckoned the Franklinists erred because they confused experimental modelling with real-world needs. Points drew lots of electrical fire from heaven—just what experimenters wanted; balls were more restrained—just what the Ordnance managers needed. "Our intention is not to make electrical experiments but by the means of conductors to preserve buildings from the dangerous effects of lightning" (Wilson 1773, 52; Mitchell 1998, 314–16). Wilson's polemic brought into the domains of ministerial politics and theatrical showmanship the implicit reasonings on which such model-making depended. Model-makers claimed they already understood the system being modelled, then used their models to investigate it. But, as Wilson sagely argued, though it might be possible for experimenters to generate precision measures of electricity in cabinet, yet it was not obvious that this precision could be maintained when the experimenters projected their model results to large-scale systems.

During the same months as the first Purfleet crisis of 1772, Franklin and his colleagues were absorbed with another, equally complex, problem in electrical modelling of the natural economy. Natural historians had long known of the existence of cramp-fish, stingrays, eels, and their ilk. Most referred their stunning effects to mechanical action—this was, for example, the favoured theory of the eminent La Rochelle naturalist René-Antoine de Réaumur published in 1714. But such shocks were also candidates for absorption by the electrical cosmologies of the mid-eighteenth century. Linnaean naturalists, for example, were convinced such effects must be electrical (Ritterbush 1964, 33, 35–39). To show that stingrays were indeed electrical, it was necessary to model them with artificial electricity, then to reconcile these model trials with anatomy and natural history. Colonial connections supplied resources for dealing with electric fish (Walker 1937, 90–92). In spring 1772, Franklin encouraged a wealthy MP, John Walsh, veteran of the East India Company administration in Madras, to start work on the European torpedo. He went to Paris and La Rochelle in summer 1772 with Leyden jars and electrometers (Franklin 1959–, 19: 160–63).[1] As the Purfleet committee started its debates, Franklin gave Walsh detailed instructions on how to show the fish was electric by substituting it in electrical set-ups for a Leyden jar. Walsh showed the La Rochelle academy that the mechanistic views of their favourite son, Réaumur, could be destroyed with English equipment and the prestige of Franklinist natural philosophy. Gathering as many fish as he could from local boatmen, performing messy anatomies and startling electrical trials, Walsh "announced the effect of the Torpedo to be Electrical, by being conducted through Metals and intercepted by Glass and Sealing wax". The Rochellais were shocked into conviction by joining in the show (Franklin 1959–, 19: 189–90, 204–6, 233–35, 285–89; Torlais 1959, 119–20). Walsh told Franklin there was not a single shock "of the torpedo that we do not most exactly imitate with the Phial". But he conceded there were striking disanalogies between the fish and the jar: "the charged phial occasions attractive or repulsive dispositions in neighbouring bodies, its discharge is obtained through a portion of air, and is accompanied by light and sound, nothing of which occurs with respect to the torpedo" (Franklin 1959–, 19: 205 and 20: 266).[2] Since the stingray did not exert distant forces nor emit sparks, several London natural philosophers rather doubted Walsh's model argument. Walsh told Franklin that "as artificial electricity had thrown light on the natural operation of the torpedo, this might in return if well considered throw light on artificial electricity" (Franklin 1959–, 20: 260; Walsh 1773). Here was just the ingenious technique also involved in the debate about lightning-rods. By using the accepted Franklinist theory of the workings of the electric phial, it was possible to show that the fish mimicked an electrical instrument. Then any differences between the instrument and the animal would be referred not to the failure of the analogy but to the incompleteness of the theory.

Walsh and Franklin needed new resources to make the stingray look like the electric phial (Ingenhousz 1775; Franklin 1959–, 20: 75–79, 433; Hamilton 1773). It was not enough to use the fish as a substitute for electrical apparatus. Such apparatus also had to be arranged to mimic the fish. In 1773 Walsh supplied London's principal anatomist, John Hunter, with torpedos from Torbay, to show that "the Leyden phial contains all [the fish's] magic power" (Walsh 1774, 473). Hunter gave public demonstrations of the fishes' electric organs, "liberally supplied with nerves" and structurally similar to columnar phials (Hunter 1773). Franklin sent Walsh's reports to eminent natural philosophers. Walsh even received the prestigious blessing of Linnaeus himself. "I cannot tell you how delighted I was by your explanation of this phenomenon", the Swedish master wrote, "because it confirms the hypothesis which I have already adopted of an electrical force in the nerves" (Franklin 1959–, 21: 148, 150).[3] The Royal Society awarded Walsh its Copley Medal. In autumn 1774 Franklin's friend John Pringle, President of the Royal Society, lectured on the medallist's work. Pringle told the Society that "between lightning itself and the Leyden phial there is no specific difference, nay scarcely a variety, why then should we multiply species and suppose the torpedo provided with one different from that which is everywhere else to be found?" (Singer 1950, 251). So the authority of the lightning model was used to make the fish model convincing.

Just as in the Purfleet episode, so in the fish experiments, model-making helped because it let experimenters exert detailed control over an artefact, and thus legitimated a bolder philosophical claim about the behaviour of natural systems. Walsh conceded that the "veil of nature" obscured the electrical organs of the fish (Franklin 1959–, 20: 267). In early 1773 he turned to his friend Henry Cavendish to lift it. Cavendish's resources included the ability to measure very small electrical quantities and a theory which distinguished electrical quantity from the electrical intensity that could then be made manifest in a model (Walker 1937, 93–101; Jungnickel and McCormmach 1996,

189–90). A large array of Leyden jars in series could deliver a comparably large amount of electricity at an intensity so low that it could not produce discharge, nor easily travel across any air gap. By building a model fish, Cavendish could bring the unmanageable and 'veiled' animal's electricity within the scope of his own accurate electrometry. Most of Cavendish's decisive measures of conductivity and electrical quantity relied on his own idiosyncratic capacity to distinguish different shocks with his own bodily responses. His fish model let him distribute in public the account of electrical discharge which he had painstakingly developed backstage. In January 1775, therefore, Cavendish gave the Society a paper describing an "artificial torpedo" (Fig. 4.2). First he tried a wooden frame containing a number of

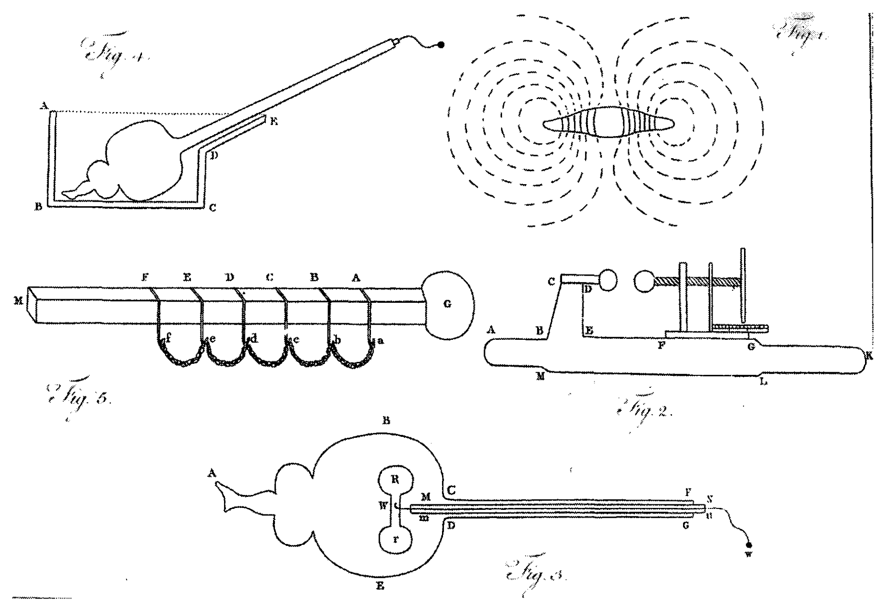

Figure 4.2 Henry Cavendish's model of an electric fish, shown in London in 1775. His figures show (1) the paths of electric fluid through water; (2) an electrometer to measure spark distances; (3) the fish model with a long wire passing through a glass tube to the internal artificial electric organ; (4) the model dipped in salt water; (5) a set-up to detect the transmission of the electric shock. Source: Henry Cavendish, "An account of some attempts to imitate the effects of the torpedo by electricity", *Philosophical Transactions* 66 (1776): 222, pl. 3. By permission of the Syndics of Cambridge University Library.

jars, then, when he reckoned this was a worse conductor than the fish itself, he built a frame of brine-soaked shoe-leather with thin pewter plates to mimic the electric organs. "The water used in this experiment was of about the same degree of saltness as that of the sea, that being the natural element of the torpedo and what Mr Walsh made his experiments with" (Cavendish 1879, 204). It was no argument against the electrical theory of the fish that it could not pass the shock through a short metal chain but that Cavendish's electric model still could. Rather, this showed that "the battery I used is not large enough" (Cavendish 1879, 211).

Cavendish's ingenious modelling did not sway his critics at once. Henly reckoned that no perfect conductor could ever behave the way the torpedo did. One Dublin commentator observed that if Walsh and Cavendish were right then lightning storms should happen underwater (Jungnickel and McCormmach 1996, 189). So in May 1775 Cavendish invited Henly, Hunter, and Priestley into the inner sanctum of his Great Marlborough Street laboratory. He showed them the model fish and let them experience its shocks. He hid the lights in his room to show the faint discharge. The implication was that previous observers of the fish had not been adequately equipped with the embodied skills and high-class instruments of Cavendish's armamentarium. Henly certainly changed his view. By 1777 he was mimicking Cavendish and Walsh in their instrumental manipulation of the electric fish. "The experiments by which Mr Walsh proves the existence and effects of this faculty are simple and elegant", the nabob's secretary recorded. "He lately repeated them publickly before numerous companies of the Royal Society and others to their great wonder and astonishment".[4] Once these witnesses had been convinced, Cavendish published his paper in the *Philosophical Transactions*. He by no means asserted that the fish's electric organs were exactly like Leyden jars, since that would violate the logic of the model argument. Instead, he used his model's success to insist on the truth of his theory of high-quantity and low-intensity electricity. By modelling the fish Cavendish institutionalised his own new account of electric agency and his practice of accurate electrometry (Cavendish 1879, 194–215, 313).

The new institutionalisation of precision and dramatic modelling was then used to win backing for pointed lightning conductors at the Purfleet magazine. Throughout 1774–77 Wilson kept this issue alive in the London press (Franklin 1959–, 21: 223). In May 1777 the Purfleet arsenal, defended according to the Franklinists' advice, was hit by lightning. In the midst of the

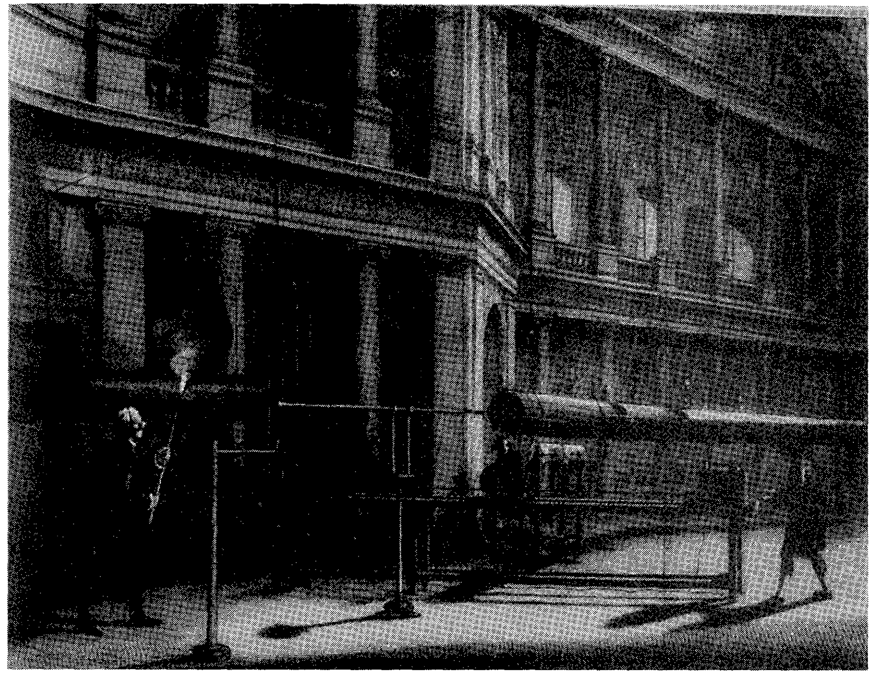

Figure 4.3 Benjamin Wilson's model of a lightning strike on the Purfleet arsenal demonstrated at the Pantheon in September 1777. Source: Benjamin Wilson, "New experiments and observations on the nature and use of conductors", *Philosophical Transactions* 68 (1778): 245–313, fig. 3. By permission of the Syndics of Cambridge University Library.

critical moment of the American war, some reported considerable damage to the navy's chief powder magazine (Boddington et al. 1778). Wilson seized his chance to get court backing for a huge new model on a scale of 1:36 (Fig. 4.3). The King was notoriously fascinated by ingenious models, whether of ships or buildings. "The plan I conceived to be the most proper for this purpose", Wilson explained, "was to have a scene represented by art as nearly similar as might be to that which was so lately exhibited at Purfleet by nature". Using royal cash and Ordnance Board equipment, Wilson modelled the arsenal and its points under a thunder-cloud with a vast prime conductor of 3,900 yards of wire and a tinfoil cylinder 155 feet long and 16 inches in diameter. He would win the fight by bulk. He used his new cylinder machine to charge the prime conductor, then recognised he would have to move the model of the arsenal under it along specially crafted grooves, since the model cloud itself was too vast to shift (Wilson 1778a, 246).

Wilson set up his model for public display at the Pantheon, opened in 1772 under crucial patronage of the King. The Pantheon was fashioned for masquerades, the modish London shows in which sublime entertainments allowed the seductive inversion of hierarchy. Wilson used his Pantheon play to seduce his audience, first the royal court, then the Ordnance Board, the Royal Society and, ultimately, the paying public with a show repeated every day during autumn 1777 (Chancellor 1925, 247–58; Brewer 1997, 60–63, 398–99; Randolph 1862, 1: 36; Mitchell 1998, 322–23). There were some puzzles due to the scale of Wilson's show. It was hard, for example, to estimate the size of vast discharges by mimicking Cavendish's celebrated sense of touch, "uncertain as it is in many cases to determine the different effects occasioned by the interposition of these different terminations", high points or low balls. Furthermore, because his enormous artificial cloud, unlike the real thing, discharged all at once and was recharged only by degrees, the model house moved very slowly under it. He put gunpowder inside the model arsenal to increase the similitude and the drama. The scale and thus theatricality were designed to show just how catastrophic the rapid and far-reaching effects of points really were. Only courtly power could afford, or engineer, such model work (Wilson 1778a, 257, 283, 306; Mitchell 1998, 323–24).

Wilson had in the late 1760s enjoyed Edmund Burke's personal support in some of his more popular artistic efforts (Randolph 1862, 1: 22). According to Burke's fashionable aesthetics, which reached a seventh edition by the end of the 1770s, events such as terrifying thunderstorms represented the height of nature's sublimity. To reproduce sublime effects through deliberate design, Burke recommended, "a true artist should put a generous deceit on the spectators ... No work of art can be great, but as it deceives: to be otherwise is the prerogative of nature only" (Burke 1987, 76). Hence arose a puzzle for the electrical model-builders. Model-makers had to spell out their artifice to make this imitation work, but too much artifice might undermine the allegedly natural, artless status of the model. This was what divided the protagonists in the lightning-rod controversy—the relationship between the measured art of the enlightened philosopher and the histrionic artfulness of the courtier. So after a disputatious visit by Henly and his Royal Society colleagues to the Pantheon in September 1777, it was reported that "this is a very unfair and unsimilar experiment" which gained its authority not

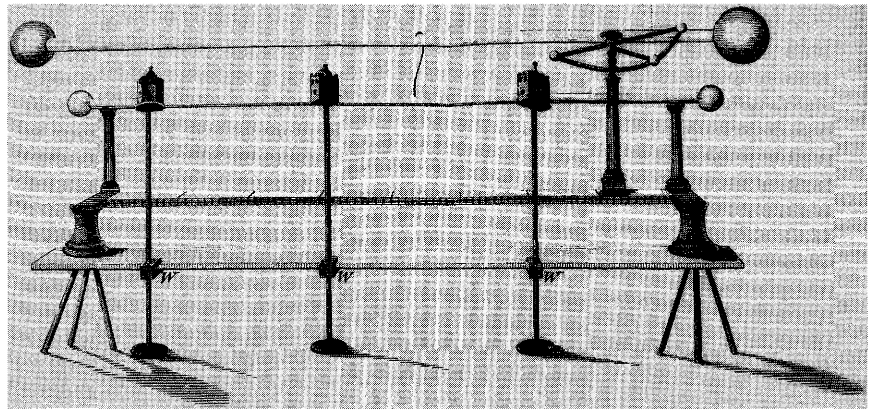

Figure 4.4 William Swift's version of the Wilson model of a thunder cloud above the Purfleet arsenal. Source: William Swift, "Account of some experiments in electricity", *Philosophical Transactions* 69 (1779): 454–61, fig. 2. By permission of the Syndics of Cambridge University Library.

from the validity of the model but the art of the show, Wilson's "apparatus of Drums and Princely Visitors".[5] Wilson's court interest tried to make the committee's views seem private, not those of the Society as a whole.

The Franklinists countered with new models (Benjamin 1896, 281–82; Franklin 1959–, 24: 163, 487–89 and 25: 5–6, 26). A Greenwich experimenter, William Swift, imitated Wilson's set-up on a much smaller scale, but with a pair of prime conductors, one positively and the other negatively charged, "to exhibit many experiments more analogous to the natural effects of lightning from the clouds ... because in nature clouds are constantly flying in the air which are differently electrified and discharging themeselves in each other" (Fig. 4.4). Swift also added an insulated vessel of water interposed above the model arsenal to imitate rainfall. He backed the orthodox view that points could draw electricity at great distances, slowly, silently, and safely (Swift 1779). In summer 1778 the prestigious instrument-maker Edward Nairne showed that a compelling model of the arsenal could be constructed without Wilson's excessive scale. Nairne's professional skill lay in rendering such small-scale models into precision instruments. Then with carefully staged spectacle, and the decision to design clouds which could themselves be moved, Nairne convinced his fellows and customers that Wilson's confessedly unwieldy and inexact 'clouds' were imperfectly insulated. Hence they exaggerated the size and speed of discharges to high pointed rods (Nairne 1778). Wilson and his allies riposted that with accurate electrometers they could prove that points drew charge from great and dangerous distances. They denied he had cunningly interrupted the communication between his model points and the ground, a circumstance which would increase the fatal drama of electric explosions as the 'cloud' passed above. There was "no juggle in making his experiments". But juggling was the key to the model-makers' artistry. Models made the sublime into the artificial, measurable, and thus manageable (Wilson 1778b; Musgrave 1778, 805).

The history of the invention of the Voltaic pile can be read as an aftermath of these 1770s debates about lightning-rods and electric fish. In May 1782 the Lombardy natural philosophy professor Alessandro Volta came to London to publicise his new condenser, which could ease experimenters' difficulties in measuring charges gathered during thunderstorms. He met Walsh and discussed Cavendish's torpedo model (Heilbron 1979, 442, 457–58). The East India Company merchant and chemistry journalist William Nicholson soon designed a version of Volta's instrument which mechanised the collection of atmospheric electricity (Volta 1782; Nicholson 1788). Volta eventually substituted Nicholson's instrument with pairs of metal discs, and began to recognise that the residual electricity in the device could help him understand the nature of animal electricity too (Gill 1976, 355–58; Pera 1992, 104–16; Kipnis 1987, 118–25, 135). Nicholson then published an article which addressed Cavendish's fishy model-building. The disanalogy between the torpedo and the Leyden jar stayed impressive, so Nicholson instead proffered his multiplier as a better model of the electric fish. Thin discs of talc when pulled apart would produce just the large quantity of low-intensity electricity apparent in the torpedo (Nicholson 1797a; Cavallo 1797; Nicholson 1797b, 358). Within months, Volta designed his own model, pairs of zinc and silver discs separated by brine-soaked paper. In March 1800 he reported to Banks that the shock generated by this pile "has a perfect resemblance to that slight shock experienced from a torpedo in an exceedingly languishing state, which imitates still better the effects of my apparatus by the series of repeated shocks which it can continually communicate". Volta explained that torpedos must simply bring together otherwise separated conducting discs to generate all their electrical effects (Volta 1800, 431; Heilbron 1977; Pera 1992, 150–58). Nicholson reproduced Volta's new pile, criticised its author for ignoring its salient chemical effects, and advertised metropolitan shops where the components for this "artificial electric organ" could be purchased (Nicholson 1800; Kipnis 1987, 135–37; Sudduth 1980, 28–29; Golinski 1992, 203–7).The demonstration of Volta's model fish, now defined as the electrical pile, by no means settled the relationship between animal, atmospheric, and artificial electricity. Rather, it launched new enterprises for modelling electrical action and claiming the right to manage living behaviour. In Regency London philosophical materialists and electrical practitioners such as the radical Francis Maceroni repeated the lesson that brains and nerves were "real electrical machines, similar in principle, as they are similar in substance and structure, to the electrical discharging apparatus of the gymnotus and the torpedo" (Morus 1998, 131). The new institutions of public sciences took over the Enlightenment project to model nature's capacities and social realities with ingenious machines.

SHIPS

Workable models seemed to offer a way of managing systems that were otherwise hard for metropolitan institutions to control. Smarting from defeat in the American war, and facing new military threats from Spain and France, British naval experts were peculiarly aware of the virtues of model structures in reforming marine design. As at the Ordnance Board, so naval architecture could be remodelled, and hence dockyard and shipboard labour reorganised. In late 1789 a veteran publisher John Sewell, with close links to the East India Company and the Thames shipbuilders, began printing manifestos for an overhaul of naval construction. He stressed "the importance of the study of shipbuilding by philosophical as well as practical men" (Sewell 1791–92, part 1: vi). Sewell was a conservative opponent of what he saw as French and radical ideas. He printed attacks on the subversive Joseph Priestley and joined the Loyal Association formed in London to counter republicanism at the start of the Revolutionary War (Nichols 1812, 3: 738; Sewell 1791–92, part 2, appendix: xxi–xxiii; Gorham 1830, 202–3). Sewell's network established a Society for the Improvement of Naval Architecture, launched in a London pub in April 1791. Their avowed precedents included the Society of Arts' ship-model trials three decades earlier, and the more recent successes of London instrument makers' demonstrations, especially those of Nairne (Sewell 1791–92, part 1: 3, 63–66). The problem with naval design was that the "business was not studied as a science, but carried on more by precedent"

(Sewell 1791–92, part 1: iv). Members included Banks, mathematicians such as Hutton, several Thames shipbuilders, and some important naval administrators, including Charles Middleton, recently departed head of the Navy Board. By the following year membership had risen to over 300 (Sewell 1791–92, part 1: 66; Johns 1910, 29–31). The Society aimed at putting before the public new models in naval administration and science. Three strategies were proposed. They would "preserve for public exhibition" exemplary ship models, "with such improvements as have been adopted on the joint opinions of able mathematicians and skilful shipbuilders". They wanted a new academy in the naval dockyards to train cadets in the mathematics of navigation and shipbuilding. They would sponsor experiments with ship models in controlled settings (Sewell 1791–92, part 1: 2, 14–15; Martyn 1791, 4–5).

The theoretical problems these experiments confronted—ship stability, hull design, and frictional drag—were more obviously urgent concerns for national security than the problems of lightning protection at naval arsenals discussed by the Ordnance Board and the Royal Society. The Royal Navy was the nation's largest technical enterprise and a centre of the fiscal-military state. Speedier and stabler ships, capable of carrying larger and more guns, were essential to British military power. But Navy Board administrators were often sceptical of costly reforms to management and schemes for allegedly better ship design (Brewer 1989, 34–37; Ashworth 1998a, 65–71; Rediker 1987, 75; Morriss 1983, 15, 31–37). Block models of standard hulls were commissioned for the Admiralty and taken from captured enemy ships whose designs were considered especially admirable. It was hard to see how to scale up these established models to full-size vessels, though London instrument-makers marketed devices which apparently helped such scaling (Franklin 1989, 49–51; Lavery and Stephens 1995, 24–25, 94–95). Throughout the eighteenth century, administrators appealed to "the authority of practice" before agreeing to fund innovation (Rodger 1993, 137–40). This was why the Society for the Improvement of Naval Architecture was so impressed by the need to replace 'precedent' with 'science'—and their new models would generate this new reason.

The major conflicts over remodelling naval architecture took place around the labour process of the shipyards. A warship would be built from a few plans made at the traditional scale of one inch to four feet. Frames taken from the midship section were composed of arcs, which were scarcely optimal

for design but easy to scale, and would be used to draw lines in the yards' mould lofts, where they would be applied to the timber (Lavery and Stephens 1995, 22–24). A moral economy existed in the vast shipyards to protect artisan skill and resist changes in wage rates. The very term 'strike' became widely used in 1768 when shipwrights paralysed the London fleet by striking its sails. Sudden mobilisation and re-equipment could easily disrupt this economy (Morriss 1983, 28–29, 60–1; Prothero 1979, 24–25; Rediker 1987, 110; Linebaugh 1991, 311). So could changes in power between private contractors and the major royal yards (Pollard 1953; MacDougall 1999). The war years saw a growth in labour militancy in yards whose military and economic value had correspondingly increased (Linebaugh and Rediker 2000, 219). In 1794 the Thames shipwrights founded their own friendly society to restrict labour supply, sustain wages, and secure workshop opacity. In 1797 Sewell established a Marine Voluntary Association to break up mutinies in the British Channel fleet. In 1798 the first Marine Police force was set up to oversee the docks (Prothero 1979, 33, 46–50; Nichols 1812, 3: 738; Linebaugh 1991, 430). Those who wished to remodel naval systems, such as Middleton at the Navy Board or Samuel Bentham as Inspector-General of Naval Works, spoke of "saving manual labour" and "ensuring greater despatch". Middleton planned a revision of the entire system of regulation of naval administration "to make each dockyard serve as a part only of a great machine" (Morriss 1983, 60, 186). In his own work for the Society of Naval Architecture, Middleton offered premiums for better models for ship design or naval administration. What might seem to some managers as rational reforms, such as steam engines in the Deptford yard in 1768, policing the loss of woodchips from Portsmouth in the 1790s, or the new well-fortified West India Docks in 1799–1802, were resisted by shipwrights as infringements of their moral traditions (Linebaugh 1991, 384, 425; Ashworth 1998a, 73–76).

The construction of ship models directly responded to the tensions of this naval system. Their everyday use in naval yards depended on collective skills judged impossible to render calculable (McGee 1999, 229). Use of models in trials and demonstrations was often taken as a sign of the incapacity of rational mechanics to describe or predict ship behaviour. The Society for the Improvement of Naval Architecture recognised the puzzle: "of two ships built by the same mould, and rigged exactly the same, one shall sail very well, and the other but indifferently" (Sewell 1791–92, part 1: vii). So the Society sought to turn "the poorer classes of workmen in the Yards" into paid experimenters (Sewell 1791–92, part 1: 3, 15). Model-building already formed a crucial element in shipwrights' traditional skilled work (Franklin 1989, 4, 177; Lavery and Stephens 1995, 35–36, 82–83). Commercial model-makers plied their trade alongside other marine instrument-makers. Models were important means of training by hands-on experience (Franklin 1989, 5; Lavery and Stephens 1995, 49; Morriss 1983, 37–38). Such models were not, therefore, so much a solution to the naval problem as a site where that problem was contested. Ingenious ship models and measured trials stood for this contest between the managerial reason of analysts and overseers and the tacit skills of the dockyards (Linebaugh 1991, 390; McGee 1999, 226).

Sewell's Society echoed a Newtonian theme in the programmatic writings of enlightened analysts of naval mechanics, the contrast between theoretical perfection and artisan ignorance. In the second book of the *Principia mathematica* (1687) Isaac Newton had set out the mechanical theory of fluid resistance which dominated academic theories of ship motion for a century. His doctrine, simplified by such writers as Emerson, implied that fluid resistance would vary as the square of the velocity of the moving body, its maximum cross-sectional area, and some constant dependent on the shape of the vessel. For a sphere, this constant was one-half. The analytic project was thus defined as the search for the highly-desirable solid of least resistance, a task well beyond and often inimical to the everyday work of shipwrights (Cohen 1974; Hall 1979, 164). Newton proposed that "by the same method by which we have found the resistance of spherical bodies in water and mercury, the resistance of other bodies can be found; and if various shapes of ships were constructed as little models and compared with each other, one could test cheaply which was best for navigation" (Newton 1972, 463; 1967–81, 6: 463). Though this proposal was omitted from all subsequent editions of the work, Newton maintained his interest in naval training as advisor to the Royal Mathematical School where boys were taught mathematics and navigation as preparation for apprenticeship at sea, and where the gradation from mechanic to mathematician was much in evidence (Newton 1959–77, 3: 359–60; Iliffe 1997).

Newton's prestigious hierarchy of mathematical reasoners and humbler artisans was an indispensable resource for enlightened theorists, especially in the French system of academic expertise and state regulation of the naval and merchant marine (Séris 1987, 132). In 1775, distinguished academicians such as Charles Bossut were commissioned by the French government to try

resistance experiments on model boats at the Paris École Militaire. Instead of complex hulls, the experimenters relied on highly simplified geometrical shapes; they took for granted the dependence of resistance on the square of these models' speeds; and they claimed that frictional effects on the sides and stern of a model were negligible (Stoot 1959, 37; Wright 1989, 316). These academicians' experiments were closely studied in London. In 1776 an East India Company engineer, Henry Watson, also arranged an English edition of Leonhard Euler's *Theory of the Construction and Properties of Vessels*, the dominant academic text on the mathematics of shipbuilding. Like his colleagues, Euler endorsed the use of "good models in miniature which represent vessels exactly as they are"; but, like them, Euler relied on simplified geometrical solids to substitute for the behaviour of ships at sea (Euler 1776, 256). In summer 1790, Sewell publicised Euler's view that "it is not necessary that the model should exactly represent the whole vessel entirely", and that "the experiments which we might easily make would lead us without difficulty to a discovery of the good or bad properties which great vessels executed according to such models, ought to have with respect to resistance" (Sewell 1791–92, part 1: 27–28).

The Society's principal experimenter was a young, wealthy, and enthusiastic member of the Society's council, Mark Beaufoy, already expert in experiments on fluid resistance (Kerr 1974, 28; Beaufoy 1930, 163). In summer 1790, just made FRS, Beaufoy wrote to Sewell criticising the Paris academicians' trials on ship models, especially their claims about the solid of least resistance and the negligible effects of stern and side friction (Beaufoy 1834, xxiv; Sewell 1791–92, part 1: 24–26). Experiments should be done "by models drawn through the water by means of weights and pullies" (Sewell 1798–1800, part 1: 29–33). Beaufoy's trials along these lines eventually cost him almost £30,000 and lasted from spring 1793 until the extinction of the Society in late 1798. William Wells, another Society member, gave him use of the large Greenland Dock, and his collaborators included naval officers, the East India dock managers Randall and Brent, and Hutton, who performed the tedious calculations to derive precise results from the data accumulated in Beaufoy's almost 2,000 separate experiments (Stanhope 1914, 172, 182–83). Like Bossut and Euler, Beaufoy constructed idealised geometrical models, rectangular planks, spherical sections, and parallelepipeds. Applying Smeaton's designs already used in the Society of Arts trials, he used measured

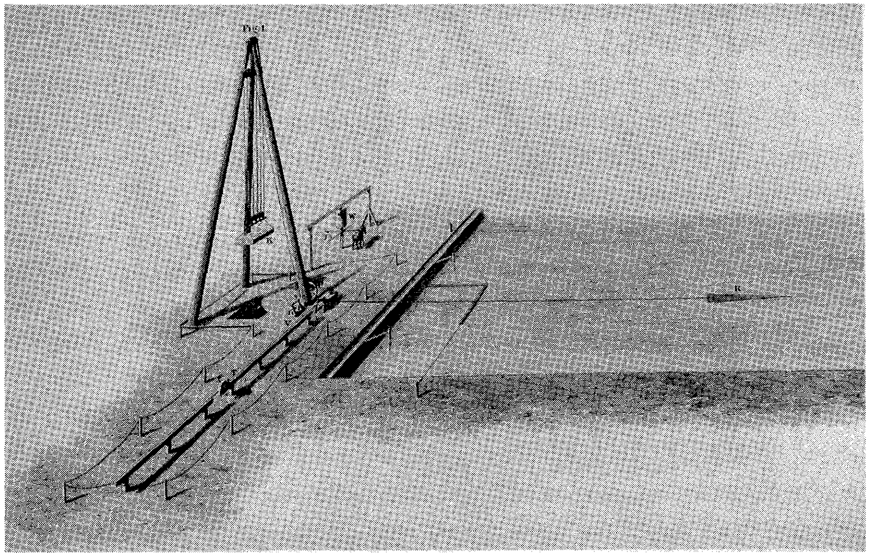

Figure 4.5 Mark Beaufoy's apparatus for dragging ship models by horse-drawn pulleys at constant speed across Greenland Dock. Source: Mark Beaufoy, *Nautical and Hydraulic Experiments* (London, 1834). By permission of the Syndics of Cambridge University Library.

weights on horse-driven pulleys to drag these models across the surface of the dock (Fig. 4.5). The resisting force was computed from these weights, and as in Smeaton's set-ups, friction became the focus. Beaufoy also designed an ingenious system for measuring speed, using a horizontal rod on a smooth pulley which moved 12 times more slowly than the model itself. By marking the rod at known time intervals, a system comparable to that of Atwood's Machine, Beaufoy could measure the speed and acceleration of his geometrical ships. From the start of 1795, his attention turned to the effects on motion when the models were submerged. By winter 1795–96 he could demonstrate that friction was a major quantifiable factor in motion (Fig. 4.6). Against the orthodoxy of Newton, Bossut, and Euler, it seemed that bow shape was not the only variable affecting ship performance. Beaufoy's collaborators helped him define fluid resistance as a combination of the pressure effects at bow and stern, plus the friction along the surface of the hull. Beaufoy introduced what he called 'friction planks' to show that in general speed varied with resistance at a power of speed of between 1.71 and 1.82, well

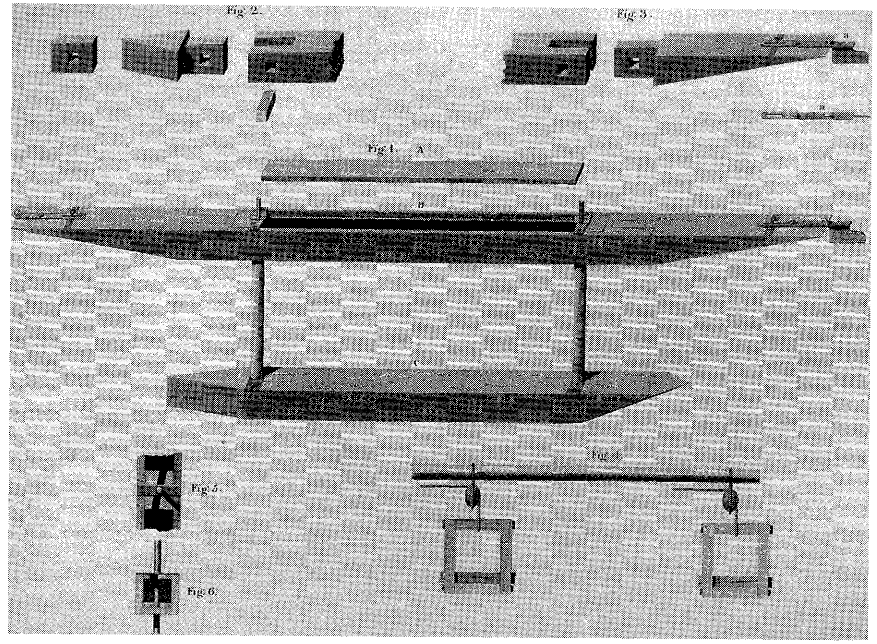

Figure 4.6 Mark Beaufoy's new friction planks to estimate the drag on ship models' motion through water. Source: Mark Beaufoy, *Nautical and Hydraulic Experiments* (London, 1834). By permission of the Syndics of Cambridge University Library.

below the Newtonian square law (Beaufoy 1834, xxvii–xxviii; Wright 1989, 317–21). Soon after Beaufoy completed his runs, his equipment was taken over by other Society members, with the aid of Wells' staff. Experimenters armed with trial data which showed that curved hulls were most stable, and that ships could be designed much longer than they were wide, hoped "that in time those absurd maxims which have so long governed the constructors of shipping will submit to refutation and be laid aside" (Gore 1799, 6). The Society advertised the extraordinary accuracy of Beaufoy's "curious and instructive" trials. "They clearly prove that experiments can now be made, by means of proper models, so as to ascertain the comparative advantages or disadvantages arising from the form . . . of all kinds of navigable vessels" (Society for the Improvement of Naval Architecture 1800, i–ii).

Yet to make Beaufoy's trial models count as exemplars of shipyard realities and then capable of changing shipwrights' ways, more was needed than the sterling efforts of the experimenters at Greenland Dock and Hutton's desk-top calculations at Woolwich. It would require an entire transformation of the labour conditions and administrative structure of the dockyards and the academies (McGee 1999, 229). Atwood's own response to the Greenland Dock work was telling. In early 1796 he finished a long survey of enlightened navigational science. He proposed large-scale tests to check differences between analytical theory and shipwrights' custom. Atwood was struck by Beaufoy's demonstrations that stern pressure and hull friction were quantifiable factors in ship motion, or at least in the motion of his geometrical solids. They showed frictional resistance must be at least a cubic equation in velocity. Atwood distinguished two senses of the term 'theory', the "pure laws of mechanics", known by academicians, and "a systematic rule which individuals form to themselves from experience and observation alone". He was prepared to credit the "experimental knowledge in naval constructions which has been transmitted from preceding times", the shipwrights' "skill and ingenuity". But analysts' difficulty in *inferring* shipyard tradition had no effects on their rights to *direct* the shipwrights. The alliance between experimental modelling and rational analysis was the only means through which the global reach of naval systems could be engineered (Atwood 1796, 125–29). Atwood was awarded the Royal Society's Copley Medal for his rules for calculating the metacentre at the large angles of heel neglected by previous analysts. Though needing as much as two years' work to apply, his unwieldy methods were adopted as guides. In early 1798, as Beaufoy's experiments were reaching completion, Atwood finished a treatise on ship stability. He claimed that the theory was "liable neither to ambiguity nor error". Nothing that happened in the shipyards or at sea had ever falsified the true theory of motion. The sole reason for the apparent inapplicability of theory was "that steady adherence to practical methods rendered familiar by usage which creates a disposition to reject, rather than to encourage, proposals of innovation in the constitution of vessels" (Atwood 1798, 202–4). Sewell published Atwood's mathematical methods, alongside Emerson's theory of the solid of least resistance, as part of the campaign to rationalise shipwrights' work (Sewell 1798–1800, part 1: 39–41 and part 3: 1–11).

Atwood's programme can be compared with contemporary attempts by Samuel Bentham and his allies at Portsmouth, where the principles of rational mechanics and precision engineering were applied to break the shipwrights' resistance and transform dockyard production lines. Bentham held that "the mode of putting together or fastening any of the component parts of that very complicated machine, a ship" would be useless without "a perfect knowledge of the principles of mechanics". From 1801 he tried to set up an apprenticeship system with teaching in these principles made compulsory and wages dependent on theoretical expertise (Ashworth 1998a, 68–69; Morris 1983, 110–12). Resistance in the dockyards was not limited to the Portsmouth strikes against Bentham's system. Atwood contacted the shipyard contractors, Randall and Brent, who had helped administer Beaufoy's trials. They supplied him with schemes of a fine East India ship to test his model of stability and loading (Atwood 1798, 287). Randall was the main supplier of ships to the East India Company. He planned his own treatise on naval architecture through the medium of the Society for the Improvement of Naval Architecture before being forestalled by Atwood and Beaufoy. In spring 1802, as the navy demobilised at the end of the Revolutionary War, Randall tried to impose a wage cut in his yards. His workers struck and Randall tried to get scab labour from the nearby Deptford royal dockyards. The Admiralty offered troops to guard Randall's yard and sacked their men who refused to work there. This was a major labour crisis of the age. During the summer Randall was hurt during a strikers' demonstration and died of his wounds. The shipwrights claimed victory: "how so large a body of men as we are could possibly resist the combinations of by far the greater part of our employers assisted by various departments of Government, civil, military and naval, is a mystery none but ourselves can develop" (Prothero 1979, 47–48; Morriss 1976; MacDougall 1999, 50–51). Unlocking the shipwrights' mystery was indeed the concern of yard managers, model experimenters, and academic theoreticians.

When Beaufoy's model data were published, they were prefaced with a hagiographic account of Randall's death during the 1802 strike (Beaufoy 1834, xxxviii). After the strike, Beaufoy continued his campaign for naval modelling. He used the popular natural philosophy journals to publicise new experiments on stability and hull design (Beaufoy 1817a, 9; Stanhope 1914, 183). Like Atwood, Beaufoy wanted the Admiralty to run model experiments using their own barges, transformed into more regularly shaped boats. Perhaps even Greenland whalers could be turned into scientific vessels. Beaufoy saw that unless ships were changed into forms more manageable by rational analysis, models could never generate useful data (Beaufoy

1817b, 257–58, 261; Beaufoy 1817c). By the end of the Napoleonic War, model-building had become more integrated into the formal system of naval training. Commissioners at the Navy Board, veterans of the Society for the Improvement of Naval Architecture, including Charles Middleton, agreed to establish a Portsmouth School of Naval Architecture. This realised the Society's plan for "a seminary at one of our principal royal dockyards" to expropriate the skills of artisans otherwise "totally incapable of paying that arduous and unremitting attention to the highest branches of mathematics" (Sewell 1791–92, part 1: 14–15). Under Cambridge-trained mathematicians, Portsmouth students studied Newtonian mechanics and algebraic geometry, read Emerson on the scaling problem in timber, and Atwood on ship stability. Special ship models were used to train the students in naval architecture. "In all the details of executing a draught from given dimensions, laying off in the mould loft and the actual building, they will not have much to learn" (Morriss 1983, 113–14, 221; Franklin 1989, 166).

But this was a controversial claim. One radical London magazine, *The Chemist*, edited by the socialist artisan Thomas Hodgskin, carried shipwrights' complaints that the School's models were designed to destroy traditional means of skill and advancement. Hodgskin's short-lived magazine was the organ of metropolitan artisan radicals fascinated by the materialist lessons of chemical philosophy and galvanism, and hostile to the pretensions of the professoriate at the Royal Institution and other homes of fashionable natural philosophy (Morus 1998, 15–16, 102; Golinski 1992, 244). The journal turned its guns on the new school of naval architecture and its model curriculum. The school's defenders might boast that "till the school's establishment *few persons* in any of our naval arsenals ever thought of guiding their practice by maxims drawn from the *legitimate* principles of science". Radical shipwrights countered that "legitimate principles" must mean "principles lawfully begotten in the cranium of some lawfully appointed professors of abstractions". The radicals directly named these detestable theorists, including Atwood himself. There was an obvious link between the legitimism of the professors and the legitimism of the reactionary regimes of postwar Europe. The shipwrights singled out for their bile "these *Holy Alliance* parts of science and the imputation thus to be cast on our best ship builders in all times, past and present". It was clear that "Calculus will not make them good ship builders". The lesson for the entire enterprise of model-building and rational science was damning.

> Let them show to the world that they possess that almost omnipotent power of determining with precision the various properties of that complex body called a ship, which even the immortal Newton thought impossible and that the person most likely in any degree to succeed was the man of practical experience.... To talk to an able practical shipwright of predicting the displacement, stability, weatherly qualities, and other essentials of a large ship by calculations made (as is the case in all calculations) from a drawing on a small scale, is only making a laughing stock of one's self. What makes the whole matter still more laughable is that the whole of their calculation of stability is founded on a centre of gravity which they assume and which may be almost any where but where they place it. What should be said of our modern theorists, who think it nowise absurd to attempt the construction of a whole navy upon nothing? (Working Shipwright 1825)

Hodgskin's radical magazine was short-lived, but so was the "laughable" Naval Architecture School. It shut in 1832, only to be replaced in the following decade by a system of shipyard schools which continued to suffer from the troublesome contrast between traditional artisan custom and formally trained expertise (Casey 1999). Training, modelling, and labour conflict stayed salient themes in the scientific regimes of the period. It has been convincingly argued that the physical sciences were established in early-nineteenth-century Britain through the combination of urban mathematical practitioners, the Cambridge professoriate, and scientifically expert members of the armed forces. The character of this coalition helped define the research agenda in astronomy, navigation, optics, meteorology, and geomagnetism. Cavendish, master of precision measures of gravitation and electricity, and Beaufoy, medallist of the new Astronomical Society, were among the heroes of this alliance (Miller 1986; Ashworth 1994). Stories of model-making in late-eighteenth-century Britain help illuminate the origins of these new sciences and their practitioners. Because models could be controlled and disciplined, they lent themselves to campaigns for precision management of society and cosmos. Institutions such as the Ordnance Board, the Royal Society, the military schools, the dockyards, and the Navy Board backed these campaigns. Inside and around these institutions, however, were groups who resisted and undermined the remodelling of practice, custom, and tradition. The evocative account of an eighteenth-century mathematician's universal paradigm and god-like power used as this essay's epigraph should be juxtaposed with that of the pseudonymous "working shipwright", who in early 1825 wrote in the London press against those who claimed "that almost omnipotent power of determining with precision the various properties of that complex body called a ship".

NOTES

1. John Walsh, Diary of Journey to France, 1772, 53–55, John Rylands University Library, Manchester, English MS 724.

2. John Walsh, "Experiments on the torpedo or electric ray at La Rochelle and l'Ile de Ré", 1772, Royal Society Library, MS 669, folio 72.

3. Carl Linnaeus to John Walsh, 16 September 1774 (copy), India Office Library MS Eur.E3.41.

4. David Davies to Francis Fowke, 26 November 1777, India Office Library, MSS Eur.E3.69.

5. J. H. de Magellan to Achille-Guillaume Lebègue de Presle, 15 September and 3 October 1777 (copies), Library of Congress, Franklin Papers.

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