From Craftsmanship to Draftsmanship

Naval Architecture and the Three Traditions of Early Modern Design

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Almost every historian of technology has used the word "craft" at one time or another. It is a term we apply to techniques in which artifacts are made by hand and eye and rule of thumb, where skills and knowledge are thought to be literally embodied in the craftsman. We use it to refer to techniques that proceed by trial and error, making no use of quantitative physical theory, so that they are consequently not "scientific." On the grounds that they are not scientific, we use "craft" as a historical category that includes all the technologies of the past. This category has, in turn, often been used as the foundation for a narrative in which a modern shift from supposedly conservative, tradition-bound craft techniques to "rational" scientific technologies marks a radical break in human history, a technological dividing line between past and present.[1]

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1. This is not just because the transformation, according to the narrative, marked a scientific revolution in technology, but because the use of science implies a rationality absent in the past, and thus an actual shift in human nature. To Lewis Mumford, for example, the shift from empirical, tradition-bound technics to technology based on science and mathematics "produced alterations in the human personality" and a "passing from the primeval state of man . . . to a radically different condition"; see *The Myth of the Machine: Technics and Human Development* (New York, 1966), 1:3. See also Edwin T. Layton, "Mirror-Image Twins: The Communities of Science and Technology in Nineteenth-Century America," *Technology and Culture* 12 (1971): 562–80, and "Scientific Technology, 1845–1900: The Hydraulic Turbine and the Origins of American Industrial Research," *Technology and Culture* 20 (1979): 64–89. For a debate about those who have presented the emergence of modern technology this way, see Michael Fores, "Transformations and the Myth of 'Engineering Science': Magic in a White Coat," *Technology and Culture* 29 (1988): 62–81; but also see Layton's response, "Science as a Form of Action," *Technology and Culture* 29 (1988): 82–92.

The story of a craft/science divide is certainly a dramatic one. We are entitled to ask, however, whether its foundations are secure. That is, we are entitled to ask whether it is either useful or accurate, even loosely speaking, to regard all premodern technologies as crafts. In fact, the category creates a historiographical problem. We know there is a difference between making a horseshoe, constructing a siege engine, and building a palace at Versailles. But when we ask what the difference is the question turns out to be difficult to answer, because lumping all the technologies of the past into the single category "craft" leaves us without the criteria we need to distinguish among them. With such a blunt conceptual tool we can neither hope to explain the lack of science we perceive in the technologies of the past nor properly understand the conditions under which a scientific approach to technology can develop.[2]

Accordingly, the goal of this article is to set out formal criteria for distinguishing among the technical activities of the past. In general, I approach the issue in terms of design. In particular, I argue that using criteria of graphic representation it is possible to distinguish three broad approaches to design prior to 1800. These I designate the craft (properly speaking), the mechanical, and the architectural traditions. Identifying these traditions, I suggest, provides a more fruitful conceptualization of premodern technology than is provided by the general notion of craft. More important, classification on the basis of definite criteria allows comparison. Comparison leads to a recognition of the significance of the architectural approach, in which the use of measured plan drawings allowed the application of mathematical, physical theory in design long before the modern era. It is by investigating the link between design, drawing, and science in the architectural tradition, I hope to show, that we can begin to explain both the promise and the problems of science in premodern technology.

To keep the discussion within limits I consider only the early modern period, taking 1800 as a rough cutoff date. I also focus on British naval architecture. This is partly because naval architecture was the first early modern technology to make use of measured plans after architecture itself, and partly because the use of measured plans in shipbuilding originated in Britain around 1586. Thereafter, the British naval dockyards became the single largest industrial organization in the world, and remained the largest industrial organization in Britain during the industrial revolution, so that the design techniques employed there are of interest in their own right.[3] At

2. On other problematic aspects of craft/science historiography, see David McGee, "Making Up Mind: The Early Sociology of Invention," *Technology and Culture* 36 (1995): 773–801.

3. David Lyon, *The Sailing Navy List: All the Ships of the Royal Navy—Built, Purchased and Captured, 1688–1860* (London, 1993), viii. See also the opening chapters of Ken Baynes and Francis Pugh, *The Art of the Engineer* (Guildford, Surrey, U.K., 1981), and David Brett, "Drawing and the Ideology of Industrialization," in *Design History: An Anthology*, ed. Dennis Doordan (Cambridge, Mass., 1995), 3–16.

the same time, there was a sustained attempt to apply quantitative physical theory to ship design, an effort that largely failed.[4] Early naval architecture thus offers an excellent opportunity to study the conditions that made it possible even to consider the application of science in design, as well as to study the difficulties that stood in the way of a scientific approach to technology in the early modern period.

Thinking about Design

Any discussion of design in the history of technology should start with what remains the dominant view, namely, the visual- or nonverbal-thinking account put forward by Edwin Layton, Eugene Ferguson, and Brooke Hindle.[5] As Layton expressed the essence of this view, "design involves a structure or pattern, a particular combination of details or component parts, and it is precisely the gestalt or pattern that is of the essence for the designer."[6] Similarly, Ferguson wrote in a famous passage that engineers work with their mind's eye, the "well-developed organ" they use to review the contents of their visual memory and form new or modified images as required.[7]

Both scholars focused on the creative, psychological aspects of design.[8] Indeed, both Layton and Ferguson considered the mental processes involved so distinctive that they could be used to separate design from science. Layton, for example, believed it could be shown that technologists employ a nonverbal mode of thought that has more in common with that of artists than philosophers, and concluded that design is "clearly distinct from philosophy, including natural philosophy."[9] In the same vein, Ferguson has described nonverbal thinking as a central mechanism in engineering design, involving perceptions that are the stock in trade of the artists and not the scientists."[10]

4. For a brief account of these efforts, see the introduction to John Fincham, *A History of Naval Architecture* (London, 1851).

5. Brook Hindle, *Emulation and Invention* (New York, 1981); Edwin T. Layton, "Technology as Knowledge," *Technology and Culture* 15 (1974): 31–41, and "American Ideologies of Science and Engineering," *Technology and Culture* 17 (1976): 688–701; Eugene Ferguson, "The Mind's Eye: Nonverbal Thought in Technology," *Science*, 26 August 1977, 827–36, and *Engineering and the Mind's Eye* (Cambridge, Mass., 1992).

6. Layton, "Technology as Knowledge," 37.

7. Ferguson, "Mind's Eye," 827–28.

8. Theorists of architectural and industrial design have also focused overwhelmingly on the psychological, now called the "cognitive," processes of design. See, for example, Omer Akin, *The Psychology of Architectural Design* (London, 1986); Brian Lawson, *How Designers Think* (London, 1980); Peter Rowe, *Design Thinking* (Cambridge, Mass., 1987).

9. Layton, "Technology as Knowledge," 36–37.

10. Ferguson, "Mind's Eye," 834.

While it would be foolish to deny the role of creative visualization in technology, there are problems with the visual-thinking account of design that limit its usefulness, at least for the purposes of this article. First, the focus is on the psychological act by which new ideas or patterns are conceived. Psychological events are notoriously difficult for historians to investigate, especially when the key is held to be subrational gestalt processes of which even the actor is unaware. Second, because it is psychological the visual-thinking model is also metahistorical, and design becomes the same exercise of nonverbal mental abilities throughout history. The visual-thinking model therefore fails to provide criteria for distinguishing among different approaches to design in different times and places. Third, the last 150 years have seen the emergence of what we agree to call the engineering sciences. If technology has become scientific and design is truly central to technology, then there must be a relationship between science and design. Unfortunately, by separating science and design the visual-thinking model leaves us without the concepts or language we need to discuss the connection between them.[11]

The beginnings of different approach to design have been put forward by design theorist J. Christopher Jones, who argues that modern design techniques are only the continuation of a tradition of design-by-drawing that emerged during the Renaissance, superseding a craft approach in which no drawings were used. This shift from "craftsmanship to draughtsmanship" took place, according to Jones, because of the advantages provided by drawings with respect to both construction and innovation.[12]

In construction, Jones argued, the use of drawings to specify dimensions in advance of production made it possible to split artifacts into separate parts, which could then be made by different people. Such a division of labor made it possible to plan things that were too big for a single craftsman to make, such as large ships and buildings, and permitted an increase in the rate of production, since an object that would take a single craftsman several days to produce could be split up into components made by different workers at the same time.[13] In short, by reducing the amount of time and labor

11. Some of these problems are also noted by Stephen Lubar in "Representation and Power," *Technology and Culture* 36, suppl. (1995): S54–S81.

12. J. Christopher Jones, *Design Methods: Seeds of Human Futures* (London, 1970), 15. Jones was one of a number of "design methodologists" writing in the sixties and seventies who believed that the growing complexity of modern technology had overwhelmed existing design techniques. Their response was to attempt a systematization of the design process, drawing on techniques of problem solving and operations research developed in World War II. Odd as it may seem, their goal was to find some way of designing modern buildings and objects to be as "fit" for their environment as craft artifacts. For a brief account of the development of design methodology, see Nigel Cross, *Developments in Design Methodology* (New York, 1984), vxii–x and 303–7. Among those who have taken note of Jones's work: Nigel Cross, *Design in Technology* (Milton Keynes, 1982); Baynes and Pugh (n. 3 above), 11–12; Lubar, 71.

13. Jones, 20–22.

involved the use of drawings led to a more economical mode of construction.[14] Interestingly, Jones illustrated this part of his argument with the plans of a warship drawn in 1670 by English naval architect Sir Anthony Deane.

With respect to innovation, Jones argued that drawing allowed the design of more complex artifacts than was possible in the crafts, because a drawing's capacity to store tentative decisions concerning one part while another part is developed enabled designers to deal with an otherwise "unmanageable, and unimaginable, degree of complexity."[15] The use of drawings also allowed a faster pace of innovation, since a designer working only with the geometrical aspects of an artifact on paper did not have to deal with real constraints of materials, labor, or even physics, and was therefore "not prevented, either by partial knowledge, or the high cost of altering the product itself, from making fairly drastic changes in design."[16] Drawing and redrawing in the absence of constraints, individual forms of greater novelty could be developed more quickly and new forms evolved more rapidly over time—something Jones and others have frequently referred to as the transference of the craft trial-and-error process onto paper.

One more aspect of Jones's thinking is highly relevant, for he also observed that the use of drawings in advance of production makes prediction a fundamental problem in design. As he put it, designers are "forever bound to treat as real that which exists only in an imagined future, and to specify ways in which the foreseen things can be made to exist."[17] In doing so they must predict the future dimensions of an artifact. They must predict that it will work as expected. They must extrapolate from the past to the future on the basis of present conditions to predict that the artifact will actually be of use. But since errors in construction are always possible, artifacts designed in the absence of real physical constraints might not work, and since conditions might well change by the time the artifact is actually made, design unavoidably entails a large amount of uncertainty and risk.

Jones's framework offers a number of advantages for the analysis of early modern design. His assessment of the role of drawings in design shifts away from a concern with the psychological act of conception toward the process by which ideas are realized. This yields a definition of design as the process by which artifacts get the dimensions they actually have.[18] Atten-

14. As also noted by Lubar, 71.

15. Jones, 28.

16. Ibid., 22.

17. Ibid., 10–11.

18. This definition is recognizably close to that of the International Council of Societies of Industrial Design, namely, "a creative activity that consists in determining the formal properties of objects that are produced industrially"; see Barry Katz, "Technology and Design—A New Agenda," *Technology and Culture* 38 (1997): 452–67, n. 7. I use "dimensions" rather than "properties" here partly to simplify the discussion and partly because dimensions were the central concern of naval architects.

tion is thereby directed to how and when artifacts get their final dimensions, rather than how they are initially conceived. In addition, Jones's model points to complexity and cost of production as factors affecting the choice of different design methods in different contexts. It also points to predictive uncertainty in the face of risks as a possible reason for the use of science in the design process. Finally, Jones provides initial criteria for the classification of two early modern traditions of design: one that used drawings and one that did not.

Given these advantages, I use Jones's framework as a template for investigation in what follows. As we shall see, however, Jones's model does require significant modifications, the most important of which is that, using his own criteria of graphic representation, we can identify not two but three early modern traditions of design.

The Craft Tradition

The first tradition of early modern design to be identified on the basis of graphic representation is one in which, at least according to Jones, no drawings are used at all. This is craft proper, the method by which the vast majority of human artifacts have been designed in human history.

In the absence of drawings, the defining characteristic of the craft approach is that craftsmen work immediately with their materials.[19] Final dimensions are determined only as the materials are actually worked and the artifact actually made. There is no separation of designing from making. The two activities take place at the same time. There is no separation of designer from maker. They are the same person.[20] Think of the potter at the wheel. Craftsmen, however, do not work with the automatic precision of machines. Rather, they compensate for errors, inaccuracies, and inconsistencies in the material as they work. They change their minds as they go along. They consider what they have done and respond to it, maintaining a feedback loop with the object in a process traditionally referred to as cutting and fitting.[21] Think of the potter again, or a carpenter fitting timbers together without using a measuring tape.

The centrality of cutting and fitting allows us to identify some further characteristics of the craft approach. One is that craft methods are inher-

19. The classic example is the blacksmith, who settles the final shape of a horseshoe only as he actually bangs on the hot metal with his hammer. Hence the craft approach has been called "blacksmith design" by some; see, for example, Lawson (n. 8 above), 12. For a modern-day account see Charles Keller and Janet Dixon Keller, *Cognition and Tool Use: The Blacksmith at Work* (New York, 1996).

20. Jones (n. 12 above), 20

21. I paraphrase Roger Newport, "Design History: Process or Product?" in *Design History: Fad or Function?* ed. Terry Bishop (London, 1978), 89–97. Jones, 19–20, makes the same point.

ently wasteful of materials, since each piece of material must start out oversize then be reduced or even thrown away if the "wasting" process is carried too far. Another is that craft methods are inherently time-consuming because of the way in which the dimensions of different parts must be slowly and gradually adjusted to each other. Craft methods also require relatively expensive labor because of the high degree of skill needed to adjust parts to each other with the least amount of waste in the least amount of time. Time, labor, and materials thus form the main constraints on craft methods, from which we may conclude that the typical context for a craft approach is one in which labor and materials are relatively cheap and production time is not a pressing concern.

Now, we can confidently reject Jones's claim that the craft approach is limited to artifacts of small size and limited complexity, involving no division of labor. Such large and complicated artifacts as wooden ships have been made by groups of craftsmen right into the twentieth century. Nevertheless, the underlying point is still valid. The larger and more complex the artifact, the more problematic the constraints of time, labor, and materials will become. Some way of dealing with these constraints must be found. One response is a lengthy apprenticeship during which craftsmen are taught how to make an object with the fewest mistakes, the least waste, at the lowest cost. To achieve these goals, some crafts make use of partial representations in the form of patterns or lasts. Some even make use of partial graphic representations.[22] Early modern merchant shipbuilders made use of "mould-lofts," for example, where rules of proportions were used to lay out full-scale representations of some of a vessel's frames. Templates (or "moulds") were then made to the drawings, frames cut to the templates, and the frames set on the keel in the yard. Long thin wooden battens or ribbands were then bent around the frames and attached to bow and stern. The dimensions of the other frames and timbers were taken off the battens and mapped out in the loft.[23]

This use of partial representations suggests a need to relax Jones's definition of crafts as employing no drawings at all. However, even the rather sophisticated case of early merchant shipbuilding conforms to the criteria of craft given above. Final dimensions were determined by a process of cutting and fitting of actual materials that took place at the same time as construction, with the partially completed vessel itself used as an instrument of its own design.

What about innovation in the crafts? Here a traditional problem has been to explain what is thought to be a slow pace of change, and a typical

22. Early Venetian shipbuilders, for example, used diagrams to determine some of the dimensions of their vessels. See Frederic Lane, "Venetian Naval Architecture around 1550," *Mariners Mirror* 20 (1934): 24–49, and *Venetian Ships and Shipbuilders of the Renaissance* (Baltimore, 1934).

23. For an illustrated description, see Basil Greenhill, *The Evolution of the Wooden Ship* (New York, 1989).

explanatory strategy has been to minimize the rational or conscious aspects of the mental processes involved and to stress the idea of craft conservatism.[24] Looking at the issues in terms of graphic representation, however, we can see the difficulty without having to refer to supposed mental states or attitudes. In the absence of drawings, there is no symbolic means of predicting whether a proposed form will work or serve its intended purpose. There is experience. However, the more radical the innovation, the less previous experience will apply, in which case the only way to see if a new kind of artifact will work is to build it. But if the only way forward is to build the artifact in question, the craftsman is thereby exposed to the potential waste of all the time, money, and materials involved. Innovation in the crafts thus involves considerable risks because the only way forward is by trial and error, by actually constructing artifacts and subjecting them to the actual conditions of use.

This analysis suggests that where time, labor, and materials are absolutely or relatively cheap we might find a great deal of craft innovation.[25] Conversely where time, materials, and labor are absolutely or relatively expensive, we would expect to find either a slow pace of change—or a change in design methods.

The Mechanical Tradition

According to Jones, drawing offered advantages with respect to construction and innovation. But he did not specifically note that different kinds of drawings are used in these two activities.[26] To work out new ideas, designers still use rough, single-view, back-of-the-envelope style sketches. To control construction, they use measured multiview plans. Intriguingly, there appears to have been a distinct separation of design traditions based on the difference between these two kinds of drawings in the early modern period. In particular, prior to approximately 1750 those engaged in the design of machines made use of single-view sketches and perspective drawings but do not appear to have made any use whatsoever of measured plans.[27] I refer to the second early modern tradition of design as the mechanical tradition, therefore, because it concerned the design of mechan-

24. See Christopher Alexander's classic *Notes on the Synthesis of Form* (Cambridge, Mass., 1964), 28–53. See also the discussion of making wagon wheels in George Sturtt, *The Wheelwright's Shop* (Cambridge, 1923), 28–53; Jones, 20; Lawson, 14.

25. Adrian Forty, *Objects of Desire: Design and Society Since 1750* (London, 1986), 88–89, observes that handicraft chair makers were able to produce many more types of Windsor chairs than more heavily invested furniture manufacturers. The enormous great variety of pottery types in the ancient world also comes to mind.

26. Jones (n. 12 above), 14–15. Baynes and Pugh (n. 3 above), 14–15, also notice this deficiency and offer a more complete typology of drawings.

27. Baynes and Pugh, 34–35.

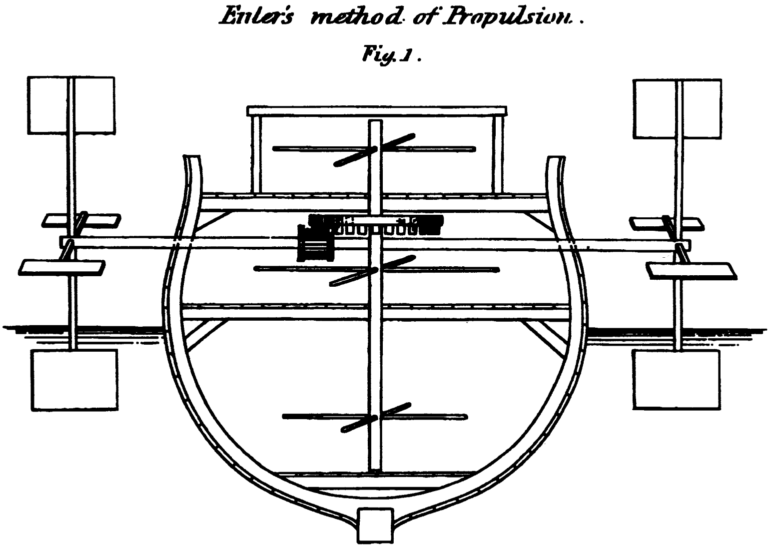

FIG. 1 Leonhard Euler's proposal for ship propulsion, submitted to a French Royal Academy competition in 1753. (John Fincham, *A History of Naval Architecture* [London, 1851], 280; courtesy of the Hart Nautical Collection, Massachusetts Institute of Technology.)

ical devices, made use of a distinct kind of drawing with definite properties, and was the precursor of the mechanical engineering of today.

The emergence of the mechanical tradition can be traced back to drawings found in the notebooks of Villard de Honnecourt, who used them to describe a number of the machines in use in the thirteenth century. Soon after, Renaissance engineers such as Guido da Vigevano, Mariano Taccola, and Francesco di Giorgio Martini realized that drawings could be used to invent as well as to describe. The Renaissance development of linear perspective was another important step, permitting the orderly investigation of machines found in the notebooks of Leonardo as well as the kind of striking presentations found in Ramelli's "theatre" of machines of 1588.[28] To get at the main features of the mechanical tradition, however, I use two later drawings (figs. 1 and 2) by Leonhard Euler and Mathon de la Cour. Both were submitted to a 1753 French Royal Academy competition on the propulsion of ships in the absence of wind.

The first thing to note is how quickly both drawings declare the purpose of the machines they depict. This is accomplished by using the principles of

28. For a survey of the early development of mechanical design drawings with references to the major works mentioned here, see Betrand Gille, *The Renaissance Engineers* (London, 1966).

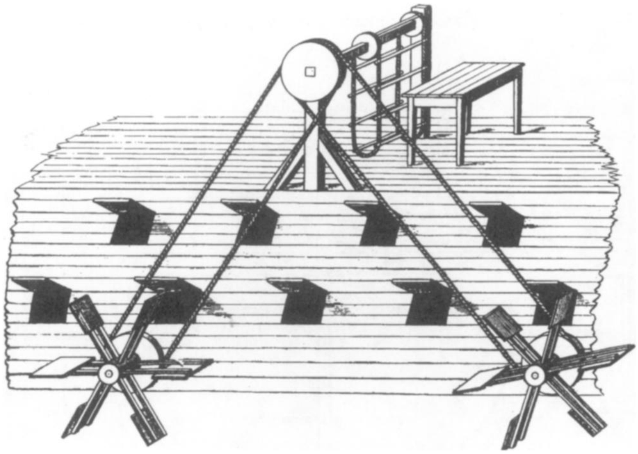

FIG. 2 Mathon de la Cour's proposed method of ship propulsion, submitted to the French Royal Academy in competition to Euler's proposal (fig. 1), 1753. (John Fincham, *A History of Naval Architecture* [London, 1851], 280; courtesy of the Hart Nautical Collection, Massachusetts Institute of Technology.)

perspective to illustrate the working arrangement involved. In Leonhard Euler's mechanism, handspikes are used to turn a vertical shaft with a toothed wheel. The wheel turns a pinion gear attached to a horizontal shaft, which rotates the paddles. In Mathon de la Cour's device, the paddles are turned by endless cords attached to pulleys, powered by a rope treadmill. In both cases, visual clarity is attained by using the conventions of perspective to show the object from a single viewpoint. Euler has complicated matters by trying to place his viewer in position to see a perfect cross section and thus "real" shapes. This created a visual problem in which the handspikes would have appeared as thin horizontal rectangles whose purpose was difficult to determine. A different viewpoint was therefore chosen from which to draw the handspikes alone, an apparent shape substituted for a real shape, resulting in a visual distortion.[29] In de la Cour's drawing, we see the top, side, and front views at the same time. Although more realistic, it is actually de la Cour's drawing that contains the greatest amount of distortion, since the use of perspective has resulted in the substitution of apparent shapes for real shapes throughout.[30] Note also that neither drawing contains any measurements.

29. The illustrations used here are taken from Fincham's *History of Naval Architecture* (n. 4 above), 280–81. Interestingly, the "distortions" in Fincham's illustration of Euler's machine are actually an attempt to correct the oddities of the original depiction, which can be seen in Leonhard Euler, "De Promotione Navium Sine Vi Venti," *Opera Omnia, Commentationes Mechanicae et Astronomicae,* ser. 2, vol. 20 (Bern, 1974), 200.

30. This analysis owes much to Peter J. Booker, *A History of Engineering Drawing* (London, 1963), 16–22.

Now, imagining that these presentation drawings came at the end of a sequence of earlier sketches, we can agree with Layton and Ferguson that they reflect the results of creative, nonverbal or visual thinking. We can also agree with Jones that such drawings provide an intuitive medium for rapid innovation because they allow the designer to work solely with the geometrical aspects of their machines, in the absence of actual constraints of time, labor, materials, or even the laws of physics. But to come to grips with the problems of the mechanical tradition, we need push the analysis a little farther than is usually done.

We can do so by recognizing that drawing and redrawing does not represent the transference of the craft trial-and-error process onto paper. In the crafts, a trial takes place when an artifact is actually built and actually subjected to the conditions of use. As long as a design remains on paper, no actual trial takes place, precisely because the drawings were created in the absence of the constraints that constitute such a trial. What has been transferred to paper is the feedback loop of cutting and fitting, as the designer draws a line here and erases a line there. And yet there is an important difference. Cutting and fitting in the crafts resulted in the *exact* determination of the dimensions of an artifact. The ersatz cutting and fitting that took place in the making of these early mechanical drawings produced only a *general* idea of form and arrangement.

The significance of this will become clear if we consider building either of these machines. Two problems immediately arise.[31] One is that no measurements are supplied, so no dimensions are actually determined. Each will have to be guessed from the drawing, a task made more difficult by the substitution of apparent for real shapes. The second problem is that not all the parts of the arrangement have been depicted: How does the horizontal shaft pass through the side of Euler's hull? What is to prevent water from leaking through the hole? How is the vertical shaft to be seated in the hold or fixed at the top? What is the diameter of the toothed wheel and how many teeth does it have? How are de la Cour's paddle arrangements joined to the hull? How is the frame for the treadmill securely fixed to the deck? The point is that in the absence of complete and final dimensions the mechanical approach to design must ultimately rely on craft methods of production. Each part will have to be shaped until all the parts fit together. New parts of the arrangement will have to be invented on the spot. Thus there can only be a partial separation of designing from making, because there is only a partial determination of dimensions in advance of construc-

31. The analysis may seem somewhat unfair since both Euler's and de la Cour's drawings were created for the purposes of presentation and not construction. As such they represent the refinement of earlier sketches, which, we may imagine, were used to work out the initial arrangements. However, both the sketches and the finished drawings have the same formal properties: no measurements, single view, etc. Hence I believe the question of building from them is not only useful but valid.

tion. There can only be a partial separation of designers from makers, since either the inventor must be present in the yard to explain what is needed or the workers must take on the designer's role by determining dimensions and adding parts themselves.[32]

All this cutting and fitting implies the same waste of time, labor, and materials associated with craft methods, but in fact the situation will likely be worse. Whereas the maker of a craft artifact spent years learning to minimize the impact of these constraints, no tradition can exist for making an invention, so that building a device from an unmeasured perspective drawing must almost certainly be more expensive than building a traditional craft artifact for the same purpose.

Given the expected costs, one would likely want to know if the device would really work before going to the trouble of building it. Can enough men be put to work at Euler's handspikes to provide enough power to move the ship? Will the wooden gear teeth stand the stress? Will the men on de la Cour's treadmill snap the ropes? Alas, even if we assume the existence of a relevant body of mathematical theory it will not help us, because there are no measurements and therefore nothing to quantify. True, we might guess at dimensions in order to make calculations. But this would be largely pointless because the cutting and fitting and adding of parts during construction would mean that the finished device would not be the same as the one from which and for which the calculations were made.[33] And even if we think the device will work, there remains the question of whether it would be of any use. For instance, Euler's paddles will not only increase resistance when the ship is under sail, the long handspikes will flail about on their own as the ship moves forward. Can a ship packed with hundreds of men be operated under these conditions?

As in the crafts, therefore, the only way to be sure a device designed in the mechanical tradition will really work or really be useful is to actually build it, knowing for certain only that it will be expensive. Indeed, the more innovative the object, or the larger the scale, the more expensive the device will be. Hence it appears that the context for the mechanical approach to design must be one in which money is no object or the need for a new solution is so pressing that cost is largely irrelevant. In either case, realization of a paper invention will require a patron with deep pockets. In the absence of

32. One can easily imagine that the details could be worked out by making a model of the apparatus. However, this would not solve the problem of determining actual dimensions. Cutting and fitting and using the artifact itself to determine dimensions would still be necessary.

33. It should be said that Euler's treatise contains all sorts of algebraic expressions intended to serve as the foundation for a mathematical theory of propulsion. I argue, however, that in the absence of initial measurements Euler's mathematical expressions were of no practical use either in predicting the behavior of the device he was proposing or in determining its final dimensions.

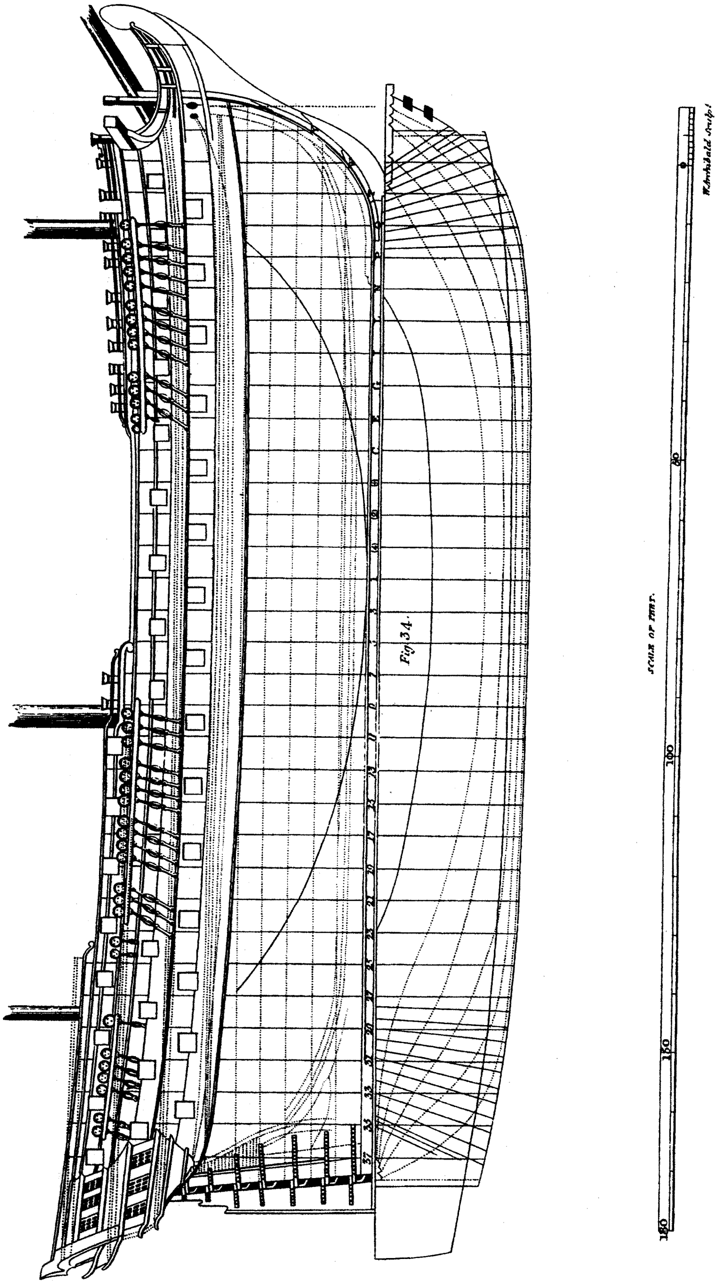

FIG. 3 Sheer plan from the article "Shipbuilding" in the 1787 *Encyclopaedia Britannica*, 2nd ed. (Courtesy of the Burndy Library, Dibner Institute for the History of Science and Technology, Massachusetts Institute of Technology.)

wealthy patrons, high costs will act as a heavy constraint on the construction of "paper" machines. This may help to explain why so few machines in the notebooks of Renaissance engineers were ever built.

The Architectural Tradition

The use of measured multiview plans defines the third tradition of early modern design, the architectural tradition.[34] It is illustrated here with a discussion of naval architecture, an approach to ship design that originated with the work of the English master shipwright Mathew Baker in the 1580s.[35] It has been argued that naval architecture was the only early modern technology (other than architecture itself) to make use of measured plan drawings until Boulton and Watt began to manufacture steam engines in the 1770s. This claim may be slightly exaggerated, but naval architecture was definitely the first.[36] However, the use of plans did not spread to merchant shipbuilding until the mid-nineteenth century, so that the term "naval architecture" prior to 1800 really only refers to the building of warships.

Figure 3 shows the kind of plans in use in naval architecture circa 1787.[37] Above is the elevation or "sheer plan." Below the line of the keel is the top or "half-breadth" plan, which, because vessels are symmetrical around their axis, shows only half the ship. Figure 4 is the "body plan," showing multiple cross sections of the hull at regular intervals along its length. The outside

34. Although, of course, architects also used perspective drawings and sketches in the early modern period, the use of measured plans distinguished their practice and thus provides a clear criterion for classification.

35. Baker's *Fragments of English Shipwrightery* is dated to 1586 and held in the Pepysian Library, Magdelene College, Cambridge. The only detailed investigation of the contents of the manuscript may be found in Stephen Johnston, "Making Mathematical Practice: Gentlemen, Practitioners and Artisans in Elizabethan England"' (Ph.D. diss., Cambridge University, 1994). For brief general accounts of design and construction in naval architecture, see Robert Gardiner, "Design and Construction," in *The Line of Battle: The Sailing Warship, 1650–1840* (London, 1992), 116–24, and Brian Lavery, *The Ship of the Line,* vol. 2, *Design, Construction and Fittings* (London, 1984), 7–27.

36. Baynes and Pugh (n. 3 above), 34–37. Ken Alder describes the slightly earlier transformation of French military production in *Engineering the Revolution: Arms and Enlightenment in France, 1763–1815* (Princeton, 1997).

37. *Encyclopaedia Britannica,* 2nd ed., s.v. "Shipbuilding." I use these drawings because they were deliberately simplified for the purposes of explanation, but they are fully representative of more complex drawings whose construction is discussed in numerous treatises on naval architecture from the period 1750 to 1822. These include: Duhamel de Monceau, *Eléméns de l'architecture naval: ou traité pratique de la construction des vaisseaux (Paris, 1758)*; Marmaduke Stalkartt, *Naval Architecture of the Rudiments and Rules of Ship-Building, Exemplified in a series of Draughts and Plans, etc.* (London, 1781); John Knowles, *Steel's Elements and Practice of Naval Architecture,* 3rd. ed. (London, 1822); and Abraham Rees, *Shipbuilding* (London, 1819).

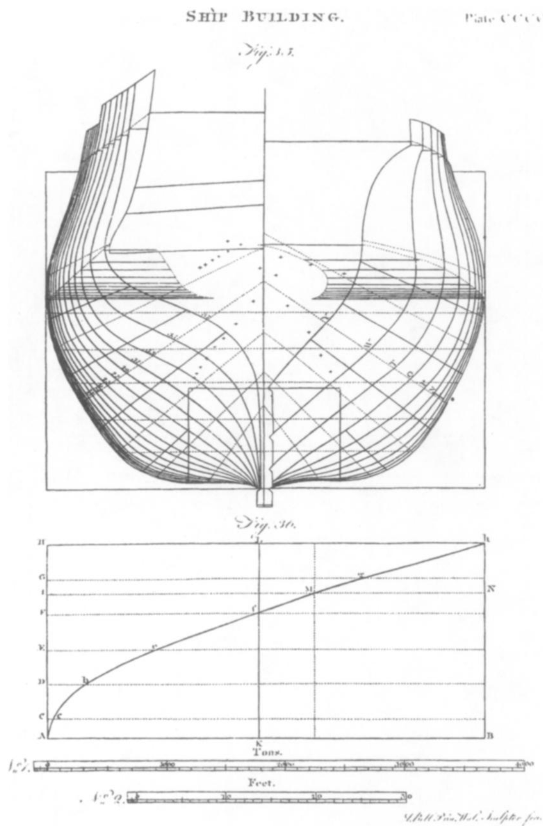

FIG. 4 Body plan from the article "Shipbuilding" in the 1787 *Encyclopaedia Britannica,* 2nd ed. (Courtesy of the Burndy Library, Dibner Institute for the History of Science and Technology, Massachusetts Institute of Technology.)

lines in the body plan represent the widest point of the vessel's hull. The lines to the right and left of center represent cross sections tapering toward the bow and stern. Each line also represents the outside shape of an actual frame whose location along the keel is shown by the straight, perpendicular lines in the other views. In contrast to the one-object, one-drawing, one-view representations used in the mechanical tradition, here we have three drawings, showing three views of a ship at right angles to each other. Each drawing and each line is intended to show true rather than apparent shapes, perspective realism being limited to inconsequential details. The results are relatively incomprehensible to the layman, in that it is extremely difficult to understand what many of the lines are for or to visualize what the shape of the hull is really going to be. But note that these are measured plans, a fact indicated by the scale found at the bottom of each drawing.

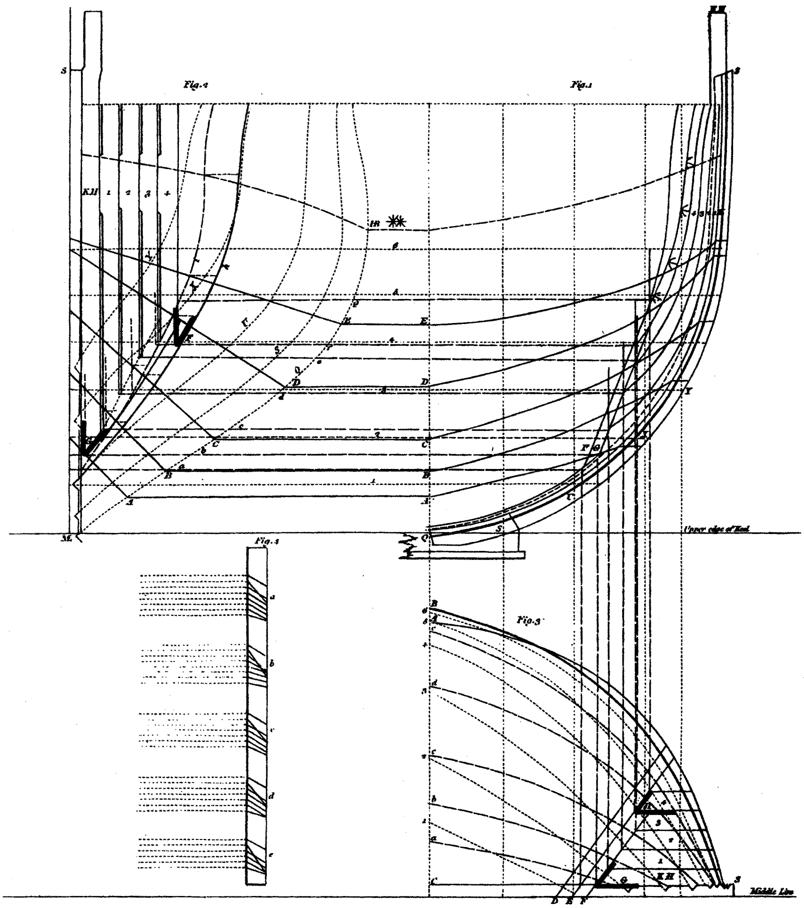

FIG. 5 Manipulation of the plans in laying-off on the mould-loft floor, with bevel board (lower left). (Abraham Rees, *Shipbuilding* [London, 1819], pl. 8; courtesy of the Burndy Library, Dibner Institute for the History of Science and Technology, Massachusetts Institute of Technology.)

According to Jones, this is the type of drawing in which final dimensions are determined in advance of construction. But nowhere near all the dimensions are actually shown. Not even every frame of the hull is represented in the body plan. These apparent omissions point to the continuing importance of the process of "moulding" carried out in the dockyard, where sections of the plans were laid out at full scale and manipulated to derive additional dimensions as necessary. Wooden templates were made to the full-scale drawings and issued to the dockyard workers who cut the various timbers to match. Moulding in naval yards, however, was carried much farther than in craft or commercial practice, extending to the determination of every part of a ship's hull. Figure 5 illustrates something of the intricacy of the procedures required to create accurate drawings of the bow and stern, where the curves of the hull were the most complex.[38]

The drawings used in early modern naval architecture therefore did contain the dimensions of every part of the hull in what might be called geometrical principle. The dimensions of the whole ship were determined before construction began. The dimensions of each part were determined before that part was made.[39] Thus a central feature of early naval architecture was a separation of designing from making, and of designers from makers. Those activities now took place at different times, and were carried out by different people. Indeed, there was also a geographical separation of design from the dockyard, since drawing plans was the prerogative of the surveyor of the navy, whose offices were located in central London.[40]

A naval architect working on paper in London is obviously not a craftsman as that term is typically understood. But it is important to recognize that the dockyard workers were no longer craftsmen either. In the crafts, final dimensions were determined only as materials were actually worked. In naval architecture, dimensions were determined in advance. In the crafts, determining dimensions meant cutting and fitting and required a creative contribution from the worker. In naval architecture, cutting and fitting was to be eliminated. The worker's task was only to make shapes determined by someone else; any creative contribution could only be a mistake, in the sense that a part altered by one worker would not fit parts made properly by others.[41]

38. See the section on laying-off in Rees. An abbreviated account appears in Jean Boudriot, *The Seventy-Four Gun Ship: A Practical Treatise on the Art of Naval Architecture*, vol. 1, trans. David H. Robert (Annapolis, 1986), 39–41.

39. It may still be objected that none of the various rooms and cabins are shown. Warships were often built and placed "in ordinary," lying in protected waters, sometimes for years, until they were needed. It was important not to install the rooms and cabins of ships lying in ordinary because the walls impeded air flow, promoting decay of the timbers. Because of this, ship design was traditionally considered to be complete once the shape of the hull had been determined. See the testimony of Sir William Rule (surveyor of the navy from 1793 to 1813) in House of Commons, "Third Report of Commission for Revising and Digesting the Civil Affairs of the Navy," *Sessional Papers, 1806, Navy (Civil Departments)* vol. 5, no. 312, 291.

40. Although the separation of designers from makers began with the introduction of plans in the seventeenth century, a complete separation of design from the dockyards did not take place until approximately 1790. The delay was due to the fact that earlier drawing techniques did not yield accurate representations of the complicated curves of the bow and stern. The details of these parts of the hull had to be worked out by the master shipwrights in the dockyards. More accurate methods of representation were developed in the second half of eighteenth century. As soon as they were adopted, the master shipwrights were forbidden to make any deviations from the plans without permission from the surveyors in London.

41. Lubar (n. 11 above), 69–73, stresses the use of measured drawings to gain control over the hands of the workers.

Indeed, it may be said that the use of plans was deliberately *anticraft*, for the goal of naval architecture was to eliminate the imprecision, the waste of material, and the waste of labor inherent in craft methods.

The anticraft nature of ships' plans points to the context in which they were employed. Size and complexity were undoubtedly important factors. But since merchant vessels of considerable size and complexity were built without measured drawings all through the early modern period, neither by itself constitutes sufficient explanation of the use of plans. Instead, the determining factor seems to have been the huge cost of warships to the state. As John Brewer points out, the fixed capital invested in early-eighteenth-century factories rarely exceeded £10,000. A first-rate three-decker of the time cost up to £40,000; Nelson's *Victory*, built in 1765, cost £63,174, and a similar ship in 1800 cost £80,000. Brewer further estimates that the total fixed capital invested in the 243 mills of the large West Riding woolen industry in 1800 was £402,650. The replacement value of the ships of the navy in the same year was £2.25 million.[42] That is, the fixed capital invested in one of the most important British industries amounted to only 18 percent of the capital needed to launch the navy, to say nothing of the huge investment made in permanent government dockyards at Woolwich, Deptford, Chatham, Sheerness, Portsmouth, and Plymouth.

Not only was the cost of building warships enormous, the expense was so much higher than anything tackled in the craft or mechanical traditions that economy of production became a crucial issue. In this light it may be seen that plan drawings were used in warship-building because they promised to save money in construction.[43]

42. John Brewer, *The Sinews of Power: War, Money and the English State, 1668–1783* (New York, 1989), 34–35.

43. Building warships was also much more expensive than building merchant vessels, where costs were simply not high enough to make the use of measured plans necessary. Space does not permit an extended discussion of the contrast between naval and commercial shipbuilding establishments, but the difference in design methods reflects different financial contexts. The costs of the Royal Navy were not just high, but a pressing political problem from the time of Elizabeth on. King Charles lost his head in part because of the taxes he imposed to pay for his navy. Succeeding Parliaments certainly demanded a strong navy but also begrudged every penny. Indeed, it was a feature of British politics that the greater the demand for naval supremacy, which could only be accomplished through greater expenditures, the greater the clamor for economy. Some response to this clamor was politically necessary, if nothing else. The use of measured plans to achieve economy in the dockyards where there was a steady demand for ships was part of that response. Commercial builders faced a rather different situation. Because their goal was to make profits, but the demand for ships was (and is) notoriously cyclical, they maintained much lower levels of capital investment in permanent dockyard plant, and it was not in their financial interest to maintain permanent design staff who might soon have nothing to do. The navy did get something for its money, however. Wooden ships built in the Royal dockyards were better built than commercial vessels, lasted longer, and cost less in repairs. It might be noted that the contrast between the staffs of naval and commercial establish-

Design and Uncertainty

As effective as plans might have been in reducing the cost of building warships, they provided a poor medium for innovation compared to the kind of sketches used in the design of machines. This was due in part to the laborious methods by which ships' plans were drawn. Instructions were generally of the type "connect *A* to *B*, make *AC* 1/3 of *AB*, raise a perpendicular, and draw the line," and so on. Hundreds of such steps followed each other in deliberate sequence as each new line was drawn in relation to lines in one view, then transferred and connected to more lines in the other two views. Each step had to be followed exactly or subsequent lines would not meet, which could lead to errors in construction. It took upward of two months to complete a ship's plans, as compared to a few minutes to sketch the outlines of an idea on the back of an envelope. Moreover, making changes had a ripple effect on the plans, in that altering a line in one view required the alteration of numerous lines in the other two views because of the geometrical relationship between them. Changing a line for the purpose of innovation thus required a methodical, time-consuming reconstruction of the plans to ensure that all the lines were still properly connected. In other words, the opportunity for the kind of drawing and redrawing found in the mechanical tradition did not exist.

A second and more important constraint on innovation in ship design was that changing lines in the plans could have highly unpredictable effects on the behavior of a ship at sea. The reasons for this require some explanation, however, beginning with the fact that naval architects in the age of wood had a very consistent list of the qualities wanted in a sailing warship. The list presented in the *Encyclopaedia Britannica* of 1787 was typical: it called for ships that sailed well, sailed into the wind, made little leeway, possessed adequate stability, pitched only moderately, and carried their guns high enough out of the water that they could be used in heavy weather.[44] Early naval architects were well aware of the hull shapes needed to secure these advantages. They knew that fine lines aft gave better steering, narrow

ments continued far into the nineteenth century. Thus in 1884 the prominent commercial shipbuilder William Denny accused William White, a naval constructor, of missing the point about newly proposed methods of calculating stability because "with all deference to the Admiralty, that Department is noted for want of what we may call economy of highly skilled labour. In a private shipbuilding yard we cannot afford such waste." The comment is instructive because Denny's firm actually had the largest design staff of any commercial builder at the time, but even he felt the pressure to economize in design. See the discussion following V. Daymard, "A New Method For Calculating, And Some New Curves For Measuring, The Stability of Ships at all Angles of Inclination," *Transactions of the Royal Institutions of Naval Architects* 25 (1884): 57–94.

44. *Encyclopaedia Britannica,* 2nd ed., s.v. "Shipbuilding," 376–77. Naval architect John Knowles gave essentially the same list, *Steel's Elements and Practice of Naval Architecture* (n. 37 above), 123.

ships sailed faster, broad ships were more stable, deep hulls reduced leeway, full bows reduced pitching, and so on. But they also knew that these desirable qualities were to one degree or another mutually exclusive, that they conflicted with each other in complicated fashion: a narrow hull results in a faster but less stable ship, full bows reduce pitching but also tend to make a ship drift to leeward, a full underwater body tends to slow a ship down but is needed for a ship that will carry guns, and so on.[45]

Given these conflicts, naval architects knew that there was no way to combine all the desirable qualities in a single ship. As the author of the *Encyclopaedia Britannica* article put it, to obtain all the desirable qualities in a ship "very opposite rules must be followed; and hence it appears to be impossible to construct a ship so as to be possessed of them all."[46] Or as John Knowles's explained in his *Naval Architecture* of 1822: "The properties which every ship ought to possess are, in a manner, subversive of, or in opposition to, each other. One figure is required for extraordinary swiftness, another for extraordinary strength or capacity; and all are regulated, more or less, by peculiar and local circumstances. The great art, however, in all places and under all circumstances, consists, in so forming the body, that none of the desired qualities shall be entirely wanting."[47] But as Knowles emphatically concluded: "to unite, in one ship, all these desirable qualities, some of which are subversive of others, is impossible."[48]

What was the designer to do in this situation? How was he to decide which qualities to keep and which to sacrifice? To this question early naval architects also had a consistent answer. According to the *Encyclopaedia Britannica*, "a ship ought to be constructed so as to answer the particular purpose for which she is intended, [and the hull] so formed, that as many of these properties may be retained as possible, always observing to give the preference to those which are most required."[49] According to Knowles, the first step in designing a ship was to "consider the various purposes that it is intended for, and the various impediments that it may meet with." Only thus could the ship be given the "arrangement of its parts and combination of its principles; especially where it will be necessary that contradictory powers shall be blended together."[50]

The difficulty, however, was that the dimensions governing sailing qualities interacted with each other in such a complicated fashion that after the

45. Jean Boudriot gives an instructive chart of these complicated oppositions in *The Seventy-Four Gun Ship* (n. 38 above), 18–22.

46. *Encyclopaedia Britannica,* 2nd ed., s.v. "Shipbuilding," 377.

47. Knowles, 121.

48. Ibid., 127. The issue of constraints, conflicting requirements, compromise, and purpose receives a lively treatment in David Pye, *The Nature of Design* (London, 1964), 73–82.

49. *Encyclopaedia Britannica,* 2nd ed., s.v. "Shipbuilding," 376.

50. Knowles, *Naval Architecture* (n. 37 above), 122.

"contradictory powers" had been blended together it was impossible to predict with certainty the behavior of the resulting vessel. Even sister ships built to exactly the same plan could have radically different sailing properties, one good, the other bad, showing that even small differences in the shape of ships could lead to large differences in behavior at sea. Samuel Pepys, secretary of the navy during the Restoration, was struck by this feature of ship design in the 1680s, thinking it "worthy of note how small things are sometimes found to mar or mend a ship's quality."[51] A century later George Atwood still stressed how seemingly trivial departures could "wholly change the qualities of a ship from bad to good, or the reverse."[52] What this degree of uncertainty meant is that naval architects could not afford to forget about real physical constraints in design in the way that mechanical designers could. Failure meant the waste of all the money spent on labor and materials. It could cost lives. In the right circumstances it could have dire consequences for the state.

Given these risks, it was a reasonable strategy, not merely a conservative instinct, to stick to designs that were known to perform well, making as few changes as possible. Just the same, since every vessel was a compromise, and something was "wrong" with every one, it was always possible that a slightly different blend of qualities would better serve the purpose. Moreover, new purposes were always arising. Contrary to received opinion, therefore, according to which wooden warships remained more or less the same from 1600 to 1850, naval architects continually altered existing designs, lengthening a bow here, adding a deck there, deepening the hold, moving the masts, and so on.[53] Uncertainty was thus a constant companion, widely recognized as the central problem in naval architecture. And it was just on the issue of uncertainty that the use of measured plans presented an intriguing possibility, namely, the prospect of using quantitative physical theory to predict the behavior of ships and thereby reduce the risk of failure.

Science and Design in Naval Architecture

In turning to the relationship between science and design in naval architecture, we are already in a position to make three points. The most

51. Samuel Pepys, *Naval Minutes* (London, 1926), 217.

52. George Atwood, "The Construction and Analysis of geometrical Propositions . . . determining the Stability of Ships, and of other floating Bodies," *Philosophical Transactions of the Royal Society* 86 (1796): 46–130.

53. On the steady pace of change, see Brian Lavery, *The Ship of the Line,* vol. 1, *The Development of the Battle Fleet* (London, 1984); Robert Gardiner, *The First Frigates* (London, 1992), and *The Heavy Frigate: Eighteen Pounder Frigates,* vol. 1, *1778–1800* (London, 1994); Andrew Lambert, *The Last Sailing Battlefleet: Maintaining Naval Mastery* (London, 1991); and David K. Brown, *Before the Ironclad: Development of Ship Design, Propulsion and Armament in the Royal Navy, 1815–60* (London, 1990).

important: drawings first, then science. Without the use of measured plans there could be nothing to quantify and so no possible application of mathematical physical theory whatsoever. The second point is that without the use of measured plans to achieve accuracy in construction there could be no point in applying scientific theory, since there could be no point in calculating the behavior of a "paper" ship if the real ship was going to be built (and therefore behave) differently—especially not when small variations in shape are known to produce large changes in behavior. The third point is that what cannot get into the plans cannot get into the ship. This is important because it gives us definite criteria for judging the utility of physical theory. Could theory affect the lines of the drawings or not?

These features of the relationship between science and design can be seen in the calculations made to determine the adequacy of a ship's displacement, really the only useful application of quantitative physical theory to the design of warships before 1800. The process began with the calculation of the weight of everything to be carried on board: iron, lead, cannon, shot, masts, sails, rigging, men, provisions, and so on. This was relatively simple because warships were classified by "rates" for which such quantities were known. Next the weight of the hull had to be calculated. This meant finding the weight of every individual timber, which, as the *Encyclopaedia Britannica* noted, was "indeed a very labourious task, upon account of the several pieces of timber, &c. being of so many different figures, and the specific gravity of some of the timber entering the construction not being precisely determined."[54] Using the plans to determine the shape, volume, and weight of each timber, however, the total weight of the hull could be found. Next, the cubic capacity of the hull below the waterline had to be calculated. This was also a laborious task because of the irregular shape of the hull. The basic idea was to use the lines of the plans to divide the hull into rectangles whose volume could easily be calculated, then find the volume of the irregular remainder by methods of exhaustion.[55] Once the volume below the waterline was known, the amount could be multiplied by the weight of a cubic foot of water to determine the displacement of the hull at the intended load line. The designer could then compare the weight of the displacement to the weight of the hull to see if they agreed.

Determining the displacement of a wooden warship was important because it could be rather dangerous to open the gun ports of a ship that rode too low in the water. Too little displacement also rendered the main battery unusable in heavy seas. But it was also important to divide the volume of the hull amidships to see if each half of the ship was equally buoy-

54. *Encyclopaedia Britannica,* 2nd ed., s.v. "Shipbuilding," 411.

55. This is a simplification. The tedious complexity of the actual methods may be seen in *Encyclopaedia Britannica,* 2nd ed., s.v. "Shipbuilding," 411–20; Rees (n. 37 above), 8–22; *Edinburgh Encyclopaedia,* s.v. "Shipbuilding," 119–28; and *Encyclopaedia Metropolitana, or Universal Dictionary of Knowledge,* s.v. "Naval architecture," 351–60.

ant, since an unevenly supported hull would begin to "hog" or bend. It might also tend to pitch heavily, working and weakening the entire wooden structure as one end plunged more deeply into the waves than the other. In fact, the *Encyclopaedia Britannica*'s calculation of the displacement of the ship represented in figures 3 and 4 showed that the aft portion of the hull was too small by 14,166 cubic feet. It therefore had to be "filled out" by 7,083 cubic feet and the fore part of the ship "drawn in" by the same amount.[56]

The interesting thing here, however, is that these seemingly precise quantities actually say very little about which lines to change in the plans in order to correct the displacement problem, or how much to move them. Should the bow be drawn in, or the fore part of the midbody? Should the water line be expanded at the stern, or the lower part of the hull near the keel? In fact, the naval architect had to choose which lines to alter by eye, bearing in mind the vessel's intended purpose. But how could the designer be sure that changes made by eye actually corrected the problem? In principle, the only way to be certain was to laboriously redraw the plans and recalculate the weight of the ship and its displacement. But if it turned out that the changes did not in fact correct the problem the designer would then be right back where he started, faced with the unpleasant prospect of redrawing and recalculating all over again.

This account of determining displacement reveals several additional features of the relationship between science and early ship design. First, scientific calculations actually gave very limited guidance to the designer on how to change the all-important lines of the plans in order to correct problems. Second, and as a direct result, the use of quantitative theory entailed the introduction of feedback loops of drawing, calculating, and redrawing into the design process. Third, if initial calculations were tedious and time-consuming, subsequent loops only added to the tedium and delay. Fourth, even if the designer completed several feedback loops this did little to achieve the overall goal of reducing uncertainty, not only because the designer eventually had to stop calculating and trust his judgment but also because the designer adjusting lines to arrive (in this case) at the required displacement was simultaneously altering the dimensions that governed the other sailing qualities. That is, the attempt to reduce uncertainty about displacement actually introduced uncertainty about the other sailing properties.

Prior to 1800 the only other property of a ship that could be calculated on acceptable theoretical grounds was stability. It could take two *years* to determine the position of the centers of gravity and buoyancy by the methods available before 1860, and then only for a single small angle of heel. But as in the case of displacement, the results did not tell the designer how to change his lines to correct a problem, nor could he be entirely sure that any

56. *Encyclopaedia Britannica*, 2nd ed., s.v. "Shipbuilding," 415.

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changes he made really corrected the problem without drawing and calculating again.[57] What all this meant was that wooden warships could be built faster than they could be calculated. Thus we see that although the use of plans in design made calculation possible, and the use of plans to ensure accurate construction gave calculation a potential value, calculations took so long and offered so little guidance that the heavy burden of computation made the employment of advanced mathematical theory in ship design rather impractical.[58]

These points are important to keep in mind because very early on the possibility of using physical theory in conjunction with ships' plans to solve problems for the state attracted the attention of many prominent natural philosophers. Thomas Harriot, Henry Briggs, and others were involved in the improvement of naval architecture circa 1600. Robert Hooke, Robert Boyle, Christopher Wren, William Petty, and even Isaac Newton made later contributions. The French took the lead in the eighteenth century as a result of the efforts of Pierre Bouguer, Daniel Bernoulli, Leonhard Euler, Charles Bossut, Jean le Rond D'Alembert and others. Together these gentlemen sought to develop theories for such things as resistance, stability, rolling and pitching. Little needs to be said about these theories, except that most of them were wrong and known to be so.[59] What is of greater interest is that many of these natural philosophers articulated the view that uncertainty in shipbuilding could be eliminated by taking a deductive approach. That is, they believed that if you started with the applicable laws of nature

57. The two-year problem is cited in Lavery, *Construction and Fittings* (n. 35 above), 25. Lavery's reference is to James A. Sharp, *A Memoir of Rear-Admiral Sir William Symonds* (London, 1858), 108 n. For early methods of calculations of stability, see *Encyclopaedia Britannica*, 2nd ed., s.v. "Shipbuilding," 420–31. More accurate but much longer and more complex methods of calculating stability are demonstrated in Atwood, "Construction and Analysis," and "A Disquisition on the Stability of Ships," *Philosophical Transactions of the Royal Society* 88 (1798): 201–310. See also Rees, 22–31; *Edinburgh Encyclopaedia*, s.v. "Shipbuilding," 121–47; and *Encyclopaedia Metropolitana*, s.v. "Naval architecture," 360–376.

58. As one commentator expressed the inutility of stability calculations: "Although mathematicians might reach, by an approximative process, the position of the centre of gravity, under the most general circumstances of form, yet from the uncertainty which hangs over the general principles of construction, but little advantage would be likely to result from it. In the British navy at the present moment, we have almost every possible variety of form; and as every alteration of form necessarily involves new consideration concerning masts and their accompaniments, and also new considerations respecting the stowage, it follows, that we cannot, without making allowances, and for which we have no precise and definite rules, apply with certainty any results that may be obtained, even to ships of that class for which the primitive calculation was made." *Edinburgh Encyclopaedia*, s.v. "Shipbuilding," 141. Naval architects only began to be relieved of the burden of calculation after 1860; see David McGee, "The Amsler Integrator and the Burden of Calculation," *Material History Review* 48 (1998): 57–74.

59. Again, see the introduction to Fincham's *History of Naval Architecture* (n. 4 above), 1851.

you could determine the proper, even the perfect, shape of a ship and eliminate uncertainty altogether.[60]

It was in this vein that the early theorist Paul Hoste complained about Colbert's campaign to improve French shipbuilding in the 1680s, writing: "It is true that for some years past, the French shipbuilders have laboured at improving their art. Some have begun to make plans, in which they have determined all the frames or models of the bow and stern; *but as they have not necessary principles, they labour with little certainty*. Their ships are not better than those which were built without the knowledge of either reading or writing; they do not sail better—often they do not carry sail so well—they rather hog—they are less durable; in a word, the constructors of the present day agree with the ancients, that *it is not yet known what the sea requires*."[61] Most of Hoste's remarks are just what we would expect. He notes that French naval constructors were moving away from the craft approach, using plan drawings to improve their art. He recognizes that the use of measured drawings did not eliminate the problem of uncertainty. But since plans are in use, he is able to suggest that mathematical science could be used by constructors to help alleviate the problem. Then he goes one step further to suggest that if constructors only knew "what the sea requires" they could begin designing on that basis, determining the shape of ships on the basis of "necessary principles."

Hoste's is a powerful rhetoric. We would all grant an ontological priority to the laws of nature and agree that a ship behaves at sea as a result of those laws. It might therefore seem plausible to think that if you understood the laws of nature you could deduce the proper shape of a ship and know precisely how it would behave. Having paid attention to the role of graphic representation in design, however, we can see why Hoste's view is mistaken. The implied sequence of design is wrong. Because the qualities desired in a sailing vessel conflict with each other, design had to start with the choice of a purpose for the vessel. This was the only way in which the architect could decide which qualities to stress, which to sacrifice, and therefore what dimensions the ship ought to have. Next, the dimensions were embodied in measured drawings. And only then could theoretical calculations be made. All of which is to say that ships do not get their shapes by "what the sea

60. A letter preserved by Samuel Pepys reports that Robert Boyle tried to develop a way to "prove the true body of a ship"; *The Private Correspondence of Samuel Pepys,* ed. J. R. Tanner (New York, 1925) 2:115. Pepys also reports Sir Christopher Wren's attempt to show "the truest figure for any body to pass through water"; *Naval Minutes* (n. 51 above), 127. The most influential (and most influentially misleading) scientist working along these lines was Sir Isaac Newton, who observed in the *Principia* that his work on the solid of least resistance "may be of use in the building of ships"; see the scholium to proposition 34, theorem 28, sect. 7 of bk. 2, *Sir Isaac Newton's Mathematical Principles of Natural Philosophy and His System of the World,* trans. Andrew Motte, ed. Florian Cajori (Berkeley, 1960), 333–34

61. Quoted in Fincham, xvi. Emphasis in the original.

requires." They get their shapes by what their purpose requires. To think you could begin designing with the laws of nature is to mistake ontological priority for the necessary sequence of the design process.

Conclusion

This article is not intended to be a history of design or a history of naval architecture, but rather an attempt at classification. Classification, of course, has its problems. The definitions always seem too sharp, the boundaries between categories too rigid. This is unfortunate but necessary for the purposes of comparison—and worth it, if comparison can help us to sharpen our thinking, shed new light on old questions, or ask new ones. Here my target has been the use of the term "craft" to apply to all the technologies of the past. My strategy has been to consider the issues in terms of design, and to consider design from the point of view of graphic representation.

One of the benefits of approaching design in this way is that it shifts attention away from the creative act with which design begins to the other end of the process by which artifacts get the dimensions they actually have, and the question becomes one of how final dimensions are arrived at rather than how patterns are conceived. Of course, there are any number of ways in which artifacts get the properties they have. The benefit of a focus on graphic representation is that it gives us a way of dealing with a potential infinity of methods in the early modern period by providing criteria for the identification of three broad traditions: the craft, the mechanical, and the architectural. This I take to be a good thing because it breaks down the association of craft with all past technics. It cannot be accurate to refer to all the technologies of the past as crafts when some (in the architectural tradition) are actually anticraft in nature. A blurring of the difference between opposing traditions cannot provide a sound basis for historical analysis. Indeed, if it can be used to include opposites it is not clear that the term "craft" means anything at all.

But further, if observably different historical technics are held to belong to one and the same category, something must be said to unite them, something not directly observable in the historical record. That something is usually held to be a characteristic way of thinking, a craft mentality. This puts the historian in the business of tracing the development of mind rather than of technics, while commitment to the idea of a craft mentality almost inevitably leads to an interpretation of the emergence of scientific technologies of the nineteenth and twentieth centuries as a shift to a more rational approach, and thus a radical shift in history because it represents an actual change in human nature. That is to say, the use of the term craft as an all-inclusive category almost compels a narrative of technical progress as mental progress.[62]

62. As discussed in McGee, "Making Up Mind" (n. 2 above).

The identification of three early modern traditions of design, on the other hand, leads away from notions of mentality by raising this question: Why should there be three? The answer must be different contexts. The comparison that classification permits reveals that designers in all three traditions faced constraints of time, labor, materials as well as problems of predictive uncertainty. Analysis also suggests that neither levels of complexity nor different kinds of constraints drive the adoption and development of new design methods, but rather different levels of cost do.[63] This is valuable partly because it recovers a place for money in thinking about design, but also because it places early modern designers in the same world as us, not a different one, giving designers reasons for using different methods. This in turn yields a narrative in which similar human beings struggle with different contexts of risk, rather than one in which different human beings ("craftsmen") struggle but fail to deal with the same context as well as we do.

Looking at graphic representation in design also yields a different way of approaching the relationship between science and technology. Most studies consider the role of science from the point of view of innovation. The comparative analysis presented here suggests that the original role for science in design was not as a source of novelty but as a means of overcoming the predictive uncertainty resulting from innovation. Comparison further reveals a need for measured plans before mathematical theory could be applied in design, first to provide the quantitative basis for physical calculations and second to ensure through accurate construction that the object calculated and the object built actually resembled each other. The case of early modern naval architecture shows, however, that even where high costs compelled the use of measured drawings problems remained to be solved. Calculations could be used to reveal problems of displacement or stability, but they were long and tedious and did not tell the designer how to alter his lines to correct those problems. Changes still had to be made by eye, according to the best judgment of the designer. In principle, any corrections then had to be recalculated, so the predictive use of scientific theory in design required the introduction of feedback loops of drawing and recalculating to the design process. But as calculations took so long for so little gain, and since the final plans still depended on the designer's judgment, there was often little value in pursuing those loops.

Many of these observations need to be confirmed by further investigation, but they do suggest an explanation for the perceived lack of science in early modern technology. The vast majority of artifacts were made in the craft and the mechanical traditions, neither of which employed the kinds of measured representations needed for the application of quantitative theory. But even in fields such as naval architecture, in which measured plans were

63. Confirming David Pye's arguments about economy, not necessity, being the mother of invention; *The Nature of Design* (n. 38 above), 34–36, 75–76.

employed, the burden of calculation was often too high for the expected benefit. Until the burden could be reduced or the benefits increased, the cheapest, fastest, and most sensible way to reduce risk in the design process was to stick as closely as possible to known models. In short, either science could not be used, or else it was not too useful.[64]

Finally, the investigation of early modern design from the point of view of graphic representation suggests a way of bridging the extraordinary gap so often posited between the craft technologies of the past and the scientific technologies of the nineteenth century. One way to cross the gap, of course, would be to say that all three traditions continue to exist today—and not just in faraway places among "primitive" peoples. Another way is to use the drawings-first, then-science principle to conceptualize two broad stages of historical development. The first saw the widespread adoption of measured drawings in the early nineteenth century, as capitalists began to act like states and heavy investments in plant led to a concomitant demand for the use of measured drawings to reduce the costs of production.[65] This laid the essential foundation for the second stage, in which, as costs continued to rise, it was recognized that measured drawings could be used to predict the behavior of machines and artifacts and thus reduce costs still further.[66]

The rapid spread of technical drawing in the nineteenth century still awaits its historian. But if the use of quantitative graphic representation is a necessary link between science and design, the distinctive feature of the nineteenth century may not be that so many technologies ceased to be crafts, or that some became scientific, but that they all became architectural.

64. This latter point was well made by Susan Faye Cannon in *Science in Culture: The Early Victorian Period* (New York, 1978), 256.

65. On the spread of drawings in the nineteenth century see Baynes and Pugh (n. 3 above), 35–37; Peter Booker (n. 30 above), 128–70; and David Brett (n. 3 above), 3–16.

66. According to this scenario we might note that by the time industries adopted the use of measured plans and found the costs and risks high enough to call for predictive calculations they were no longer crafts. Indeed, according to the criteria set out in this article no craft industry could ever turn directly into a scientific technology for the simple reason that by the time it came to be scientized it was no longer a craft.