The Social Construction of Technological Systems

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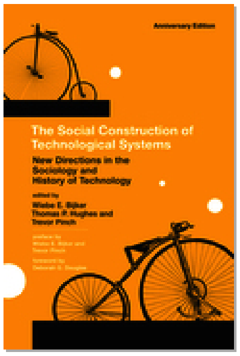
Published by The MIT Press



Anniversary Edition

The Social Construction of Technological Systems

New Directions in the Sociology and History of Technology

edited by
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Technology and Heterogeneous Engineering: The Case of Portuguese Expansion

John Law

If you want to learn how to pray, go to sea.
—Portuguese proverb, quoted by Diffie and Winius (1977)

How do objects, artifacts, and technical practices come to be stabilized? And why do they take the shape or form that they do? In this chapter I advocate and exemplify an approach to these questions that stresses (1) the heterogeneity of the elements involved in technological problem solving, (2) the complexity and contingency of the ways in which these elements interrelate, and (3) the way in which solutions are forged in situations of conflict. This "network" approach draws on and parallels work by Callon (1980 and this volume) and is developed in relation to secondary empirical material about the technology of the fifteenth- and sixteenth-century Portuguese maritime expansion. In order to clear the ground and situate my argument, I start by commenting briefly on two alternative approaches to the social study of technology.

The first approach is sometimes called social constructivism.[1] This outgrowth of the sociology of science assumes that artifacts and practices are underdetermined by the natural world and argues that they are best seen as the *constructions* of individuals or collectivities that belong to social groups. Because social groups have different interests and resources, they tend to have different views of the proper structure of artifacts. Accordingly, the stabilization of artifacts is explained by referring to social interests that are imputed to the groups concerned and their differential capacity to mobilize resources in the course of debate and controversy. Social constructivists sometimes talk of this process as one of "closure." Closure is achieved when debate and controversy about the form of an artifact is effectively terminated.

The merits of the social constructivist approach are obvious. Many artifacts are, indeed, forged in controversy and achieve their final form when a social group, or set of groups, imposes its solutions on other interested parties by one means or another. The fate of the electric vehicle in France (Callon, this volume) is amenable to such analysis, as are such other cases as the British TSR-2 aircraft (Law 1985), the Concorde aircraft (Feldman 1985), the third airports of London and Paris (Feldman 1985), the bicycle (Pinch and Bijker 1984 and this volume), and aspects of the development of missile guidance systems (MacKenzie, this volume).[2] Indeed, it is easy to think of examples. Whenever there is controversy, the contingent and constructed nature of artifacts becomes manifest, and explanations in terms of differential power and social interests become attractive.

The second approach, which comes from the history of technology and in particular from the work of T. P. Hughes (1979a, 1983, this volume), understands technological innovation and stabilization in terms of a systems metaphor. The argument is that those who build artifacts do not concern themselves with artifacts alone but must also consider the way in which the artifacts relate to social, economic, political, and scientific factors. *All* these factors are interrelated, and all are potentially malleable. 2 The argument, in other words, is that innovators are best seen as system builders: They juggle a wide range of variables as they attempt to relate the variables in an enduring whole. From time to time strategic problems arise that stand in the way of the smooth working or extension of the system. Using a military metaphor, Hughes talks of these problems as reverse salients, and he shows the way in which entrepreneurs tend to focus on such problems and juxtapose social, technical, and economic variables as they search for a solution.

Hughes's study of Edison illustrates both the systemic nature of much technological activity and the importance of the notion of a reverse salient. Edison's problem (his reverse salient) was simultaneously economic (how to supply electric lighting at a price that would compete with gas), political (how to persuade politicians to permit the development of a power system), technical (how to minimize the cost of transmitting power by shortening lines, reducing current, and increasing voltage), and scientific (how to find a high-resistance incandescent bulb filament). That Edison succeeded in resolving this set of problems reveals his success as a system builder, and it also shows that, as Hughes puts it, "the web is seamless"—that the social was indissolubly linked with the technological and the economic.[3]

The social constructivist and systems approaches have much in common. First, they concur that technology is not fixed by nature alone. Second, they agree that technology does not stand in an invariant relation with science. Third, and most important, they both assume that technological stabilization can be understood only if the artifact in question is seen as being interrelated with a wide range of nontechnological and specifically social factors. However, when they specify the relationship between the technological and the social, they start to diverge. Social constructivism works on the assumption that the social lies *behind* and directs the growth and stabilization of artifacts. Specifically, it assumes that the detection of relatively stable directing *social interests* offers a satisfying explanation for the growth of technology. By contrast, the systems approach proceeds on the assumption that the social is not especially privileged. In particular, it presupposes that social interests are variable, at least within certain limits. Although it is true that even on this point the two approaches are starting to reveal some degree of convergence,[4] the basic difference remains: In the end the sociologists prefer to privilege the social in the search for explanatory simplicity, whereas many historians have no such commitment.[5]

In this paper I join forces with Callon and side with the historians in this particular argument. Specifically, I want to suggest that in explanations of technological change the social should not be privileged. It should not, that is, be pictured as standing by itself *behind* the system being built and exercising a special influence on its development. Although it may at times be an important—indeed the dominant—factor in the growth of the system, this is a purely contingent matter and can be determined only by empirical means. Other factors—natural, economic, or technical—may be more obdurate than the social and may resist the best efforts of the system builder to reshape them. Other factors may, therefore, explain better the shape of artifacts in question and, indeed, the social structure that results. To put this more formally, I am arguing, in common with Callon (this volume, 1980b, 1986), that *the stability and form of artifacts should be seen as a function of the interaction of heterogeneous elements as these are shaped and assimilated into a network*. In this view, then, an explanation of technological form rests on a study of both the *conditions* and the *tactics* of system building. Because the tactics depend, as Hughes has suggested, on the interrelation of a range of disparate elements of varying degrees of malleability, I call such activity *heterogeneous engineering* and suggest that the product can be seen as a *network* of juxtaposed components.[6]

As is obvious, this network approach borrows much from Hughes's system-building perspective. There is, however, at least one important way in which it differs from Hughes's approach, and this difference arises from the emphasis within the network approach on conflict. Thus, as the example of the Portuguese, or indeed those of Edison or Renault, reveals, successful large-scale heterogeneous engineering is difficult. Elements in the network prove difficult to tame or difficult to hold in place. Vigilance and surveillance have to be maintained, or else the elements will fall out of line and the network will start to crumble. The network approach stresses this by noting that there is almost always some degree of divergence between what the elements of a network would do if left to their own devices and what they are obliged, encouraged, or forced to do when they are enrolled within the network. Of course, some of these differences are more pressing than others. For the purposes of analysis, however, the environment within which a network is built may be treated as hostile, and heterogeneous engineering may be treated as the association of unhelpful elements into self-sustaining networks that are, accordingly, able to resist dissociation.

This suggestion has an important methodological implication: *It makes sense to treat natural and social adversaries in terms of the same analytical vocabulary.* Rather than treating, for instance, the social in one way and the scientific in another, one seeks instead to follow the fortunes of the network in question and consider its problems, the obduracy of the elements involved in those problems, and the response of the network as it seeks to solve them. As one moves from element to element, no change in vocabulary is necessary; from the standpoint of the network those elements that are human or social do not necessarily differ in kind from those that are natural or technological. Thus the point is not, as in sociology, to emphasize that a particular type of element, the social, is fundamental to the structure of the network; rather it is to *discover* the pattern of forces as these are revealed in the collisions that occur between different types of elements, some social and some otherwise. It is to this task that I now turn.[7]

The Struggle between Cape Bojador and the Galley

In 1291 Ugolino and Vadino Vivaldi set sail from Genoa in two galleys, passed through the Pillars of Hercules "ad partes Indiae per mare oceanum," and vanished, never to be seen by any European again (Diffie and Winius 1977, p. 24; Chaunu 1979, p. 82). In 1497 Vasco da Gama sailed from the Tagus in Lisbon. He too was headed for the Indes by way of the ocean, but unlike the brothers Vivaldi we know what became of his expedition. On May 20, 1498, he anchored in the Calicut Road off the Malabar Coast of southwest India. He entered into negotiations with the Samorin of Calicut about trading in spice. So unsuccessful were these talks that on his second expedition in 1502 da Gama's now heavily armed fleet bombarded the town of Calicut in an effort to force the Samorin into submission (Parry 1963, p. 153). The Portuguese spice trade had begun and with it their domination of the Indian Ocean. I want to suggest that the process that led to this domination can be looked at from the standpoint of system building or heterogeneous engineering. Sometimes the opponents were people, and sometimes they were natural objects. Let me start, then, by talking of galleys.

The galley was primarily a war vessel. It was light and maneuverable, a method for converting the power of between 150 and 200 men into efficient forward motion. In order to reduce water resistance, the galley was long and thin—typically, at least in Venice, about 125 feet in length and 22 feet wide, including outriggers (Lane 1934, p. 3). The hull was lightly sparred, and the planks were laid in carvel fashion, edge to edge to minimize water resistance. The galley was also low. The oarsmen pulled, three to an oar, on between twenty-five and thirty oars on each side. The vessel also carried one mast (possibly more than one, see Landstrom 1978, p. 52), stepped well forward, which carried a triangular lateen sail. This sail assisted the oarsmen, although it was never more than an auxiliary source of power. The ship was steered by means of one or two rudders, and the stern was slightly raised into a "castle." By contrast, the bow was low and pointed, being designed to ram other ships. A typical galley is illustrated in figure 1.

Now let me state the obvious: The galley is an *emergent phenomenon;* that is, it has attributes possessed by none of its individual components. The galley builders associated wood and men, pitch and sailcloth, and they built an array that floated and that could be propelled and guided. The galley was able to associate wind and manpower to make its way to distant places. It became a "galley" that allowed the merchant or the master to depart from Venice, to arrive at Alexandria, to trade, to make a profit, and so to fill his palace with fine art.

The galley is, of course, a technological object. Let me, then, define technology as a family of methods for associating and channeling other entities and forces, both human and nonhuman. It is a method, one method, for the conduct of heterogeneous engineering, for the construction of a relatively stable system of related bits and pieces with emergent properties in a hostile or indifferent environment.

When I say this, I do not mean that the methods are somehow different from the forces that they channel. Technology does not act as a kind of

Figure 1

A galley (Girolamo Tagliente, *Libro Dabaco che Insegnaa fare ogni Ragione Mercantile* (Venice: Raffinello, 1541), 53).

traffic policeman that is distinct in nature from the traffic it directs. It is itself nothing other than a set of channeled forces or associated entities. Thus there is always the danger that the associated entities that constitute a piece of technology will be dissociated in the face of a stronger and hostile system. Let us, therefore, consider the limitations of the galley.

THE TRAFFIC ITSELF

As a war machine in the relatively sheltered waters of the Mediterranean the galley was a great success. As a cargo carrying vessel, however, it had its drawbacks. Its carrying capacity was extremely limited. The features that made it a good war ship—it was slim and low and could carry a large crew that might repel boarders—were an impediment to the carriage of cargo (Lane 1973, p. 122; Denoix 1966, p. 142). Furthermore, the *endurance* of the galley was restricted by the size of its crew. It could not pass far from the sight of land and the possibility of water and provisions. Although the Venetians and the Genoese used galleys to transport valuable cargoes, where reliability was called for, they were replaced in this role by the "great galleys" after about 1320 (Lane 1973, pp. 122, 126).

It must have been in such vessels that the brothers Vivaldi left Genoa in 1291 for what they thought would be a ten-year trip to the Indes (Diffie and Winius 1977, pp. 24–52). Perhaps their galleys were larger than normal, precursors of the great galley. Perhaps they had higher freeboards. But their endurance would have been limited and their seaworthiness doubtful—

one can imagine all too well the consequences of running into a storm off the Saharan coast. And, if indeed the Vivaldis were attempting to row down the west coast of Africa, then they would have had to pass what may be regarded as a point of no return—Cape Bojador, or the Cape of Fear. Chaunu summarizes the problem presented by Cape Bojador:

> At twenty-seven degrees north, Cape Bojador is already in the Sahara, so there could be no support from the coast. The Cape is 800 kilometres from the River Sous; the round trip of 1,600 kilometres was just within reach of a galley, but it was impossible to go any further without sources of fresh water, except by sail. In addition there were the difficulties . . . [of] the strong current from the Canaries, persistent mists, the depths of the sea bed, and above all the impossibility of coming back by the same route close hauled. (Chaunu 1979, p. 118)

How brave, then, were the Vivaldi brothers and their men when they sailed their galleys past the pillars of Hercules and out of recorded history! We do not know in what form disaster finally struck. What we can guess, however, is that the galleys, emergent objects constituted by a heterogeneous engineer, were dissociated into their component parts. The technological object was dissolved in the face of a stronger adversary, one better able to associate elements than the Italian system builders. It was a conflict between two opponents, a trial of strength, in which part of the physical world had the final say. Accordingly, it is a paradigmatic case of the fundamental problem faced by system builders: how to juxtapose and relate heterogeneous elements together such that they stay in place and are not dissociated by other actors in the environment in the course of the inevitable struggles—whether these are social or physical or some mix of the two. And it also suggests why we must be ready to handle heterogeneity in all its complexity, rather than adding the social as an explanatory afterthought, for a system—here the galley—associates everything from humans to the wind. It depends precisely on a combination of social and technical engineering in an environment filled with indifferent or overtly hostile physical and social actors.

↓ WEATHER

The Portuguese versus Cape Bojador: Closure and Lines of Force

In the struggle between the Atlantic and the galley, the Atlantic was the winner. We might say that the forces associated by the Europeans were not strong enough to dissociate those that constituted the Atlantic. The heterogeneous engineers of Europe needed to associate and channel more and different forces if they were to dissociate such a formidable opponent and put its component parts in their place. So for over a hundred years Cape Bojador remained the point of no return. Where were the new allies to come from? How might they be associated with the European enterprise?

Three types of technological innovation were important.[8] The first of these took the form of a revolution in the design of the sailing ship in the fourteenth and early fifteenth centuries. The details of this revolution remain obscure, circumstantial, and in any case beyond the scope of this essay, but the result was a mixed-rigged seagoing vessel (figure 2) that had much greater endurance and seaworthiness than its predecessors, one that was able to convert winds from many directions into forward motion. There were no rowers, so manpower was reduced, and it was thus possible to carry sufficient stores to undertake a considerable passage without foraging. This, then, was the first step in the construction of a set of allied entities capable of putting the North Atlantic in its place. The second was the fact that the magnetic compass became generally available in Christian Europe in the late twelfth century. I consider methods of navigation in a

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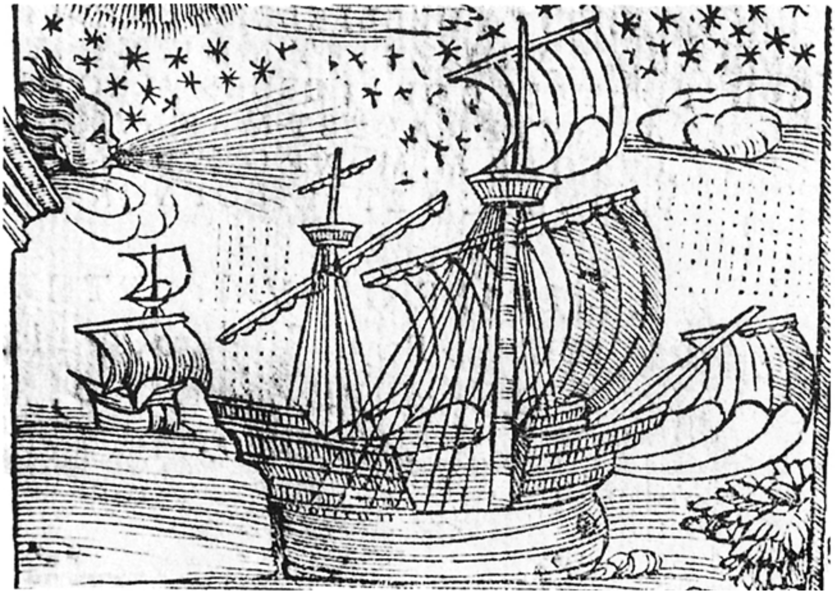


Figure 2
Large late fifteenth-century or early sixteenth-century mixed-rigged vessel (frontispiece from a 1537 Venetian edition of Johannes de Sabrosco's *Sphera volgare nouamente tradotte*).

later section, but here it should be noted that the initial importance of this innovation was that it allowed a reasonably consistent heading to be sailed in the absence of clear skies. Combined with dead reckoning and a portolano chart,[9] the magnetic compass took some of the guesswork out of long-distance navigation, and in particular it meant that the sailor did not need to hug the coast to have some idea of his location. This, then, was the second decisive step toward a change in the balance of forces. When new ships combined newly channeled winds with new methods of navigation and consequent knowledge of position, the ground was prepared for a possible change in the balance of power.

What was the decisive third step? To answer this question, we must know a little about the currents and winds between Portugal and the Canaries. It is relatively easy to sail from Lisbon or the Algarve in a southwesterly direction along the Atlantic coast of Africa. The ship is carried along by the Canaries current and is also carried before the northeast trade winds, which are particularly strong in summer. So far, then, the forces of wind and current assist the project of the sailor. It is, however, more difficult to make the return journey for precisely these same reasons. In a ship good at beating to windward, it is no doubt possible to make some northeasterly headway. But this requires frequent tacking, something that was difficult in the square-rigged ships of the day, which could not, in any case, sail close to the wind. Although the wind blows from the southwest for a period in the winter, thus making the return journey easy (Diffie and Winius 1977, pp. 61, 136), at some unrecorded point sailors decided to try to put the adverse winds and currents to good use by beating out to seaward, away from the Moroccan coast, for it turns out that, so long as one has an appropriate vessel, some means of determining a heading, and an appropriate dose of courage, it is much easier to return to Lisbon or the Algarve this way than by the coast. The vessel sails on a northwesterly heading close hauled against the northeasterly trades. It is gradually able to take a more northerly course as the trades are left behind until the westerlies and North Atlantic drift are encountered, when it becomes possible to head east in the direction of Iberia (Chaunu 1979, pp. 111–115). It was the invention of this circle, called the *volta* by the Portuguese, that marks the decisive third step. Ships were no longer forced to stay close to the coast. Cape Bojador, the classic point of no return, was no longer the obstacle it had previously been. The masters could sail beyond it and expect to be able to return.

The *volta* can thus be seen as a geographical expression of a struggle between heterogeneous bits and pieces assembled by the Portuguese system builders and their adversaries, that is, the winds, the currents, and the capes. It traces on a map the solution available to the Portuguese. It depicts what the Portuguese were able to impose on the dissociating forces of the ocean with the forces they had available. It shows us in a graphic manner how the Portuguese were able to convert the currents, winds, and the rest from opponents into allies and how they were able to associate these elements with their ships and navigational techniques in an acceptable and usable manner.

Now we begin to see the advantages and the drawbacks of the systems metaphor in an empirical context. The metaphor stresses heterogeneity and interrelatedness, but it also tends to direct attention away from the *struggles* that shape a network of heterogeneous and mutually sustaining elements. System builders try to associate elements in what they hope will be a durable array. They try to dissociate hostile systems and reassemble their components in a manner that contributes to what is being built. But the particular form that (dis-)association takes depends on the state of forces. Some of these are obdurate: Currents and winds cannot be tampered with, such is their strength. Some of them are manipulatable, but only with difficulty. Here, for instance, the square-rigged ship and navigational practices, although not immutable, were difficult to influence. Others, however, may be more easily altered. In this case the course sailed by the vessels on their return journey was a matter for discretion as a result of the advances in shipbuilding and navigation of the previous 150 years. Here there was, in the most literal sense, new room to maneuver. The course was no longer rigidly overdetermined for the system builder. Accordingly, the *volta* may be seen as tracing the state of forces and measuring their relative strengths in a literal way. It re-presented the state of shipbuilding, the state of navigation, the state of seamanship, and their collision with the forces of nature. The *volta* was the extra increment of force that allowed the new network to be stabilized, for the course was suddenly the most malleable element in the conflict between the Portuguese desire to return to Lisbon and the natural forces of the Atlantic.

The Caravel and the African Littoral: Closure and Adaptation

Africa, as the Portuguese were to discover, does not reduce to Cape Bojador. The capacity to get round the cape and then return to European waters was all very well, but there was more coastline to explore. South of the cape the coastline becomes even more inhospitable until the Senegal River and Black Africa are reached.

For most of this tricky exploration the Portuguese made use of caravels. Although the origins of this type of vessel are shrouded in mystery (Landstrom 1978, p. 100; Chaunu 1979, p. 243; Parry 1963, p. 65; Unger 1980, pp. 212–215), its fifteenth-century features are well known. Weighing less than 100 tons and being perhaps 70 to 80 feet from stem to stern (Parry 1963, p. 65), the caravel was unusual in being a long sailing ship, having a length-to-breadth ratio of between 3.3 and 3.8 to 1 (Diffie and Winius (1977, p. 118) suggest 3 to 1). It was carvel built, quite light and fine in lines, and drew little water, having a flat bottom and little freeboard (Parry 1963, p. 65; Denoix 1966, p. 143; Landstrom 1978, p. 100). It had only one deck and indeed was sometimes even open or only half-decked. There was no forecastle, and the superstructure of the poop was modest, at best containing one room (Parry 1963, p. 65). In the mid-fifteenth century and certainly on the early voyages of discovery, the caravel normally appeared to have been lateen-rigged on all its masts.

We might say that the caravel was well adapted to the context of offshore exploration. Thus we might note (as have many historians, for example, Denoix (1966, p. 142)) that for such a task one needs a vessel that will not blunder into reefs, is light and handy, draws little water, sails well against the wind, and does not require a large crew. All these attributes were true for the caravel, which was indeed well adapted to its task. But what are we really saying when we say this?

The answer to this question can be found in the notion of a network. System builders seek to create a network of heterogeneous but mutually sustaining elements. They seek to dissociate hostile forces and to associate them with their enterprise by transforming them. The crucial point, however, is that the structure of the network reflects the power and the nature of both the forces available and the forces with which the network collides. To say, then, that an artifact is well adapted to its environment is to say that it forms a part of a system or network that is able to assimilate (or turn away) potentially hostile external forces. It is, consequently, to note that the network in question is relatively stable. Again, to say of an artifact such as the caravel that it is adaptable is to note that a network of associated heterogeneous elements has been generated that is stable because it is able to resist the dissociating efforts of a wide variety of potentially hostile forces and to use at least some of these forces by transforming them and associating them with the project. And this, of course, is precisely the beauty of the caravel in the fifteenth-century context in which it was used by the Portuguese. Properly manned and provisioned, it was able to convert whatever the West African littoral might direct at it into controlled motion and controlled return. It was a network of people, spars, planks, and canvas that was able to convert a wide range of circumstances into exploration without falling apart in any of the numerous ways open to vessels when things start to go wrong. Like the *volta,* then, the caravel achieved stability by reflecting the forces around it. It was well adapted because it maintained stable relations between its component parts by associating everything it encountered with that network as it moved around.

Navigation and the Raising of the Sun: Closure and Metrication

Between 1440 and 1490 the Portuguese explored most of the West African coast. As they moved further south and used increasingly larger *voltas*, the Portuguese saw their problems of navigation become more acute. How could they determine their position when they were so far from land? Because the classical European methods of compass course, plain chart, and dead reckoning were of little assistance, this problem was of great concern to the Portuguese. In the 1480s they developed a practical method for the astronomical determination of latitude on board ship. The general idea was that if the *altura,* or height above the horizon, of the sun or a star (normally the Pole Star) could be determined and compared with the known altura of the port of destination, then the ship could sail north or south until it reached that latitude, and then sail, as appropriate, east or west in the certainty of finding its point of destination.

The measurement of the altura was possible with the use of either the quadrant or the astrolabe. Both devices were standard university instruments of astronomy and astrology that carried a great deal of information that was both unnecessary to the calculation of latitude and simply incomprehensible to the layman. On the back of the astrolabe there was, however, an alidade, which was a rule on a swivel with two pinhole sights. The observer held the instrument upright by a swivel suspension ring, peered along the alidade, and measured the altura of the star by reading off the position of the alidade on a scale marked on the rim (figure 3). The quadrant was an instrument with similar functions. It was in the form of a quarter circle, and the star sight was taken along one of the "radii." The artificial horizon was provided by a plumb line suspended from the center of the "circle" and was measured with a scale along the circumference (Taylor 1956, pp. 158–159). In its university and astrological version the quadrant, like the astrolabe, also carried information about the movements

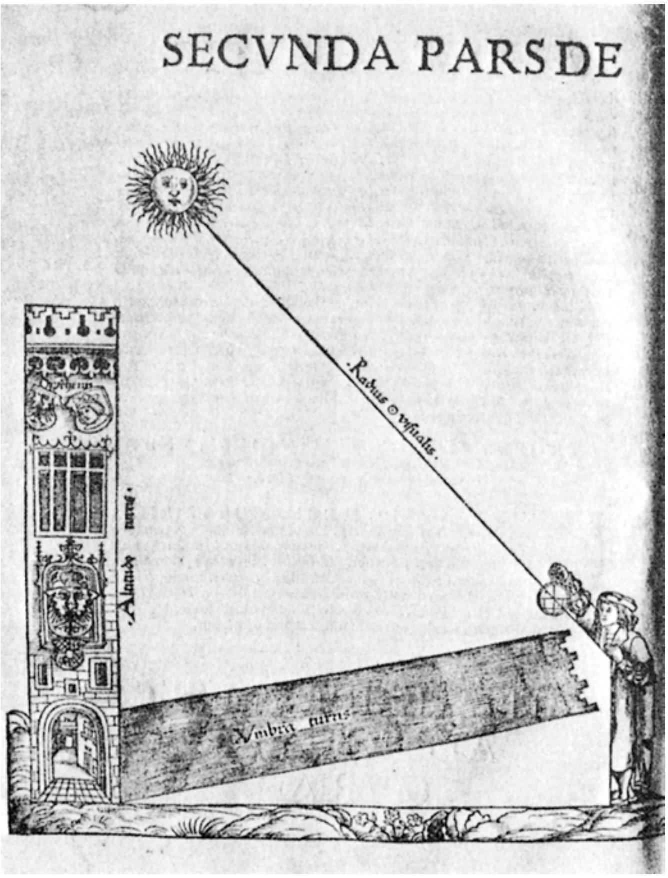


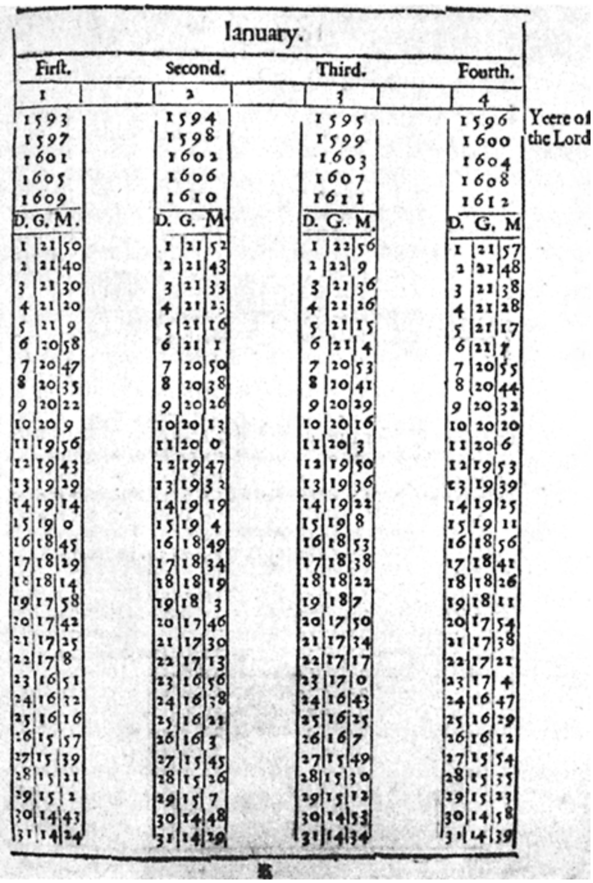
Figure 3
Measuring the altura with an astrolabe (from Sebastian Muenster, *Organa Planetarum* (Basel: Petrus, 1539), 70).

of planets, seasons, and hours. Both of these instruments, shorn of all but their essentials for the measurement of altura, were used by Portuguese explorers, although it seems that the somewhat simpler quadrant was the first to be used by navigators (Taylor 1956, p. 159).

By themselves these instruments were, of course, powerless. The mere fact of sighting a heavenly body through the pinholes of an alidade had nothing per se to do with navigation. That sighting, or the reading that corresponded to it, had to undergo a number of complex transformations before it could be converted into a latitude. The construction of a network of artifacts and skills for converting the stars from irrelevant points of light in the night sky into formidable allies in the struggle to master the Atlantic is a good example of heterogeneous engineering.

I have already mentioned the simplification of the quadrant and astrolabe. This can be treated as the first step in the process.[10] The second stage involved what may be treated as social engineering—the construction of a network of practices that, when associated with the instruments themselves, would lead to the necessary transformations of sun and starlight. This social engineering itself came in three stages. First, in the early 1480s King John II convened a "scientific commission" to find improved methods for measuring the altura. This was made up of four experts: the Royal Physician, Master Rodrigo; the Royal Chaplain, Bishop Ortiz; the geographer, Martin Behaim; and Jose Vizinho, who had been a disciple of the astronomer Abraham Zacuto of Salamanca (Chaunu 1979, p. 257; Taylor 1956, p. 162; Beaujouan 1966, p. 74; Waters 1980, pp. 9–10). The convocation of a "scientific commission" for the purpose of converting esoteric scientific knowledge into a set of widely applicable practices is already remarkable. Even more noteworthy is the fact that these four men, and probably in particular Vizinho, were able to effect that transformation by producing a set of rules for the calculation of the latitude by semieducated mariners. These rules, which form the second part of this experiment in social engineering, took the form of the *Regimento do Astrolabio e do Quadrante,* which was probably available from the late 1480s, at least in handwritten form. The *Regimento* can be read as instructions about how to turn the vessel and its instruments into an observatory—how, in other words, to create a stable if heterogeneous association of elements that had the property of converting measurements of the altura into determinations of the latitude (figure 4).

Even this, however, was not enough. To adopt the new method of sailing, the navigators required a third step: It was necessary to know the latitudes of important coastal features and in particular the major ports and capes. It was, in other words, necessary to generate a *metric* from which the observations might be given absolute north-south meaning and from which the observatory of the ship could be located accordingly. The measurement of important coastal latitudes again involved a major organizational effort. It involved sending out competent observers armed with large wooden astrolabes on the vessels of exploration and having them report back to Lisbon. By 1473 the astronomers in Lisbon had a list of latitudes that reached the equator (Taylor 1956, p. 159), a list that was extended as the century wore on. And it further required that known latitudes be available to mariners, and indeed, a further section of the *Regimento* listed these.



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12	19	43	12	19	47	12	19	50	12	19	53	
13	19	29	13	19	32	13	19	36	13	19	39	
14	19	14	14	19	19	14	19	22	14	19	25	
15	19	0	15	19	4	15	19	8	15	19	11	
16	18	45	16	18	49	16	18	53	16	18	56	
17	18	29	17	18	34	17	18	38	17	18	41	
18	18	14	18	18	19	18	18	22	18	18	26	
19	17	58	19	18	3	19	18	7	19	18	11	
20	17	42	20	17	46	20	17	50	20	17	54	
21	17	25	21	17	30	21	17	34	21	17	38	
22	17	8	22	17	13	22	17	17	22	17	21	
23	16	51	23	16	56	23	17	0	23	17	4	
24	16	32	24	16	38	24	16	43	24	16	47	
25	16	16	25	16	21	25	16	25	25	16	29	
26	15	57	26	16	3	26	16	7	26	16	12	
27	15	39	27	15	45	27	15	49	27	15	54	
28	15	21	28	15	26	28	15	30	28	15	35	
29	15	2	29	15	7	29	15	12	29	15	23	
30	14	43	30	14	48	30	14	53	30	14	58	
31	14	24	31	14	29	31	14	34	31	14	39	

Figure 4
Tables of solar declination from a navigational manual (Pedro de Medina, *The Arte of Nauigation* (London: Thomas Dawson, 1595), 58).

The new method of navigation proved difficult for most mariners. Only the most up-to-date sailors attempted its practice, and there is evidence that Columbus, among others, understood it only imperfectly. Although the details remain unclear, it appears that in the early sixteenth century, and possibly earlier, classes on navigation were taught to pilots at Lisbon (Diffie and Winius 1977, p. 142). Such instruction, however, was not invariably successful. There were complaints in the sixteenth century that many pilots were inexpert. It seems, then, that in the attempt to create a stable network of elements for the conversion of stars into measurement of the latitude—in other words, in the attempt to convert ships into observatories—it was the mariners who constituted the weakest link. The stars were always there, as were the oceans; they could not be budged. Again, once the instruments and the inscriptions were in place, they proved to be fairly durable. But instruments, inscriptions, and stars were not enough. Part of the association of elements to convert stars into latitudes lay in the practices of the mariners, and it was this element that was the most prone to distortion. It was difficult, although not ultimately impossible, to create a new social group necessary for closure: the astronomical navigator.

So far I have tacitly made the assumption that, when success is achieved, it is obvious. If one arrives at one's port of destination (or for that matter runs aground on the reefs of Cape Bojador), the success (or failure) of the enterprise is readily apparent to all. We might say that in the ultimate analysis it was the capacity of the Portuguese to *return* to their point of departure that marked success. The success of astronomical navigation was that it contributed to that return. Yet, however much final closure depended on the capacity to return, decision making on the voyage would not have been possible without a scale of reference. The success of any course sailed could be measured in the interim only against an entirely man-made metric, a metric that depended on inscriptions and the capacity to interpret those inscriptions. We have, then, the construction of a background against which to measure success—something akin to if not identical with the technological testing tradition described by Constant in the context of water turbine engineering (Constant 1983). The history of navigation can, I believe, be understood as the construction of more (locally) general systems of metrication against which the adequacy of particular courses and navigational decisions might be measured.

The Muslim and the Gun: Dissociation

On July 8, 1497, Vasco da Gama's fleet weighed anchor in the Tagus River and set sail. His four tiny vessels carried 170 men and 20 cannons. They also carried merchandise. Two years later two of the original four vessels returned to Lisbon. The cape route to India had been opened, and spices had been brought back.

The Portuguese encountered various difficulties, which arose in part from the hostility of Muslim traders in India (Magalhaes-Godinho 1969, p. 558). Such merchants organized and controlled the Indian Ocean section of the spice trade. They bought spices in the Calicut bazaars and shipped these, through either the Persian Gulf or the Red Sea, to Arabian ports for further shipment to the Mediterranean and Venice. Not surprisingly the Muslims did not welcome the arrival of da Gama on the Malabar coast at Calicut with enthusiasm. Negotiations went badly between the Portuguese and the Hindu ruler of Calicut, the Samorin. There were many reasons for this, but the most important appears to have been the hostility of the Muslim traders on whom the Portuguese were obliged to depend for translation. The translators spread a variety of hostile rumors about the Portuguese, who were then forced to trade directly with Hindu merchants (Diffie and Winius 1977, pp. 182–183).

Once back in Lisbon, the Portuguese pondered the lessons to be learned. One conclusion that they were quick to draw was that it would be necessary to exercise force in the Indian Ocean. Da Gama's first expedition had carried guns, but more would be needed if the hostility of the Muslims was to be mastered. In fact, the Portuguese had come to this conclusion even before da Gama's return. A much larger and more heavily armed second expedition had already set out; the expedition consisted of thirteen vessels and between 1000 and 1500 men and was commanded by Pedro Cabral. Cabral's orders were clear: He had to install an agent to buy spices in Calicut and was instructed to display force when this was necessary, although he was to refrain from conquest (Magalhaes-Godinho 1966, p. 561). Although negotiations started well, things quickly went wrong again. In response, Cabral put to sea, destroyed a number of Muslim vessels, and bombarded the town of Calicut. The story was repeated with da Gama's second expedition, which, however, used even more force. Together these first three sorties cast the die for Portuguese control of the Indian Ocean over the next few years. Control would have to be maintained primarily by force, as there was no room for both Muslim and Portuguese commerce.

At sea the Portuguese were, at least in the short run, able to exert the necessary military power and choke Muslim maritime trade. Portuguese guns proved better (but not more numerous) than Asian guns. European advances in the technology of gun making had overcome many of the problems that beset the late medieval cannon. In particular, with the development of cast bronze guns, the weight of the cannon had been much reduced, and although still prone to heaviness, they were much less likely to blow up in the faces of the gunners than the welded pieces that preceded them. Again, Portuguese vessels, built for the inhospitable Atlantic, were more solid than those of their Muslim adversaries (Boxer 1953, p. 196). Cipolla puts it this way:

> The gunned ship developed by Atlantic Europe in the course of the fourteenth and fifteenth centuries was the contrivance that made possible the European saga. It was essentially a compact device that allowed a relatively small crew to master unparalleled masses of inanimate energy for movement and destruction. (Cipolla 1965, p. 137)

The cannon, the ship, the master, the gunner, the powder, and the cannonballs—all these formed a relatively stable set of associated entities that achieved relative durability because together they were able to dissociate the hostile forces encountered without being dissociated themselves. It is important to note here that some of these hostile forces were physical (the oceans), whereas others were social (the Muslims). Technology, as I have suggested, simultaneously associates and dissociates, and the heterogeneous engineering of the Portuguese was designed to handle natural and social forces indifferently and to associate these forces in an appropriate form of closure.

Having said this, however, it is important not to fall into the trap of technological determinism and assume that it was the technology alone that brought about Portuguese success. As was the case for the caravel, the *volta,* and the practice of astronomical navigation, the durability of the armed warship was a function of a collision between the forces of the Portuguese system builders and those of the seas and, in this case, the Muslims. Thus Boxer (1953, pp. 194–197) argues that the Portuguese "naval and military superiority, where it existed, was relative and limited." It happened that there was no well-armed Muslim shipping in the Indian Ocean. It happened that the Chinese had retired to their coasts. It happened that the Portuguese expeditions were state enterprises, combining the power and organizational ability of the crown with the search for profit. It happened that Muslim merchants traded on their own account and not for their monarchs. It happened that there was little wood available to many of those monarchs in order to build fleets to stop the Portuguese. Under these circumstances the Portuguese were able to dominate shipping in the Indian Ocean. They were not able (and knowing this never sought to) build up sizable colonies on land. There, with the balance of force weighted against them by cavalry and manpower, they risked crushing defeat.

Conclusion

I started by outlining three approaches to the social study of technology. One, that of social constructivism, comes from the sociology of science. I suggested that, although this has many merits, its commitment to a form of social reductionism is unsatisfactory. The second, the systems approach, comes from the history of technology. This stresses the heterogeneity of technological activity and avoids a commitment to social (or technological) reductionism. I argued that this approach, adapted in a way that makes it clear that systems are built, through a struggle, from indifferent or hostile elements, offers a satisfactory model for the analysis of technological innovation. I suggested that "heterogeneous engineers" seek to associate entities that range from people, through skills, to artifacts and natural phenomena. This is successful if the consequent heterogeneous networks are able to maintain some degree of stability in the face of the attempts of other entities or systems to dissociate them into their component parts. It follows from this that the structure of the networks (or systems) in question reflects not only a concern to achieve a workable solution but also the relationship between the forces that they can muster and those deployed by their various opponents. I might, if I were to make more use of the metaphor of force, write of the relative durability or strength of different networks or of different parts of the same network. Thus I have attempted to show by empirical example that, in the collisions among different networks, some components are more durable than others and that the successes achieved by one side or the other are a function of the relative strength of the components in question.

What are the virtues of physical metaphors such as force, strength, and durability? Let me say, first, that I am not strongly committed to these terms. Doubtless other metaphors might serve as well or better. I believe, however, that the strength of the vocabulary lies in its capacity to handle, using the same terms, the various heterogeneous elements that are normally assembled within any system. As I indicated earlier, the method seeks to deal with the social, the economic, the political, the technical, the natural, and the scientific in the same terms on the grounds that (in most empirical cases) *all* of these have to be assembled in appropriate ways if closure is to be achieved. Within any of these (usually distinguished) categories, there may be entities, processes, bodies, objects, institutions, or rules that turn out to have force with respect to the system in question and hence are relatively durable. These may take the form of scientific truths, economic markets, social facts, machines, or whatever. They form, then, a relatively coercive (albeit ultimately revisable) scenery that has to be mastered if a system is to be built. Because, however, durability does not reside in one category alone, I have ignored conventional distinctions among categories, and in particular I have argued that it is not good enough to add the social as an explanatory afterthought. The social (including the "macrosocial") has, rather, to be placed alongside everything else if the collisions and closures between forces and entities are to be understood.

Like Callon, I have thus sought to press the principle of symmetry (Bloor 1976) further than is normal in the sociology of science. In the sociology of science this principle states that the same *type* of explanation should be used for both true and false beliefs. It is intended to counter the tendency commonly found in the sociology of knowledge of explaining true beliefs in terms of the way in which they correspond with reality while leaving false beliefs to be explained in terms of the operation of psychological or social factors. The generalized version of the principle of symmetry (Callon 1986) that I have adopted here states that the same type of explanation should be used for all the elements that go to make up a heterogeneous network, whether these elements are devices, natural forces, or social groups. In particular, the principle of symmetry states that the social elements in a system should not be given special explanatory status.[11] The form that these elements take may be, and often is, a function of the technological or natural features of the system. This is a contingent matter, a function of which components of the system are associated most durably and are hence least susceptible to dissociation.

To say this is not, of course, to suggest that it is always the social that is malleable and the technological or the natural that is durable. It is rather to stress that the relationship between them is one of contingency and that it is important to find a way of treating all components in a system on equal terms. But this leads to a further way in which the network approach is distinguished from that of social constructivism. In social constructivism natural forces or technological objects always have the status of an *explanandum*. The natural world or the device in question are never treated as the *explanans*. They do not, so to speak, have a voice of their own in the explanation. The adoption of the principle of generalized symmetry means that this is no longer the case. Depending, of course, on the contingent circumstances, the natural world and artifacts may enter the account as an *explanans*. And in case it is thought that I am giving too much away to realism, let me say that, so long as we are concerned exclusively with networks that are being built by people, then "nature" reveals its obduracy in a way that is relevant only to the network when it is registered by the system builders. It is not, therefore, that nature is being promoted to some special status. Rather it is, as I have already suggested, that the social is being demoted. In the network approach *neither* nature nor society has any role to play unless they impinge on the system builder.

This is why, in my explanation of the Portuguese expansion, capes and currents are found alongside vessels and mariners. Once the principle of generalized symmetry is adopted, they cannot be excluded. Indeed, to try to reduce an explanation of the Portuguese system to a limited number of social categories would be to fail to explain the specificity of the *volta,* the caravel, or the *Regimento*. Portuguese views of the sun and the adverse winds are needed to make the explanation work.[12]

A further methodological principle follows from this. It is that the scope of the network being studied is determined by the existence of actors that are able to make their presence individually felt on it. If the system builder is forced to attend to an actor, then that actor exists within the system. Conversely, if an element does not make its presence felt by influencing the structure of the network in a noticeable and individual way, then from the standpoint of that network the element in question does not exist. It is clear that the choice of network on which to focus is therefore crucial. If the focus is on one system, then one pattern will emerge. If the focus is on another system or even on an element within the original system, then a different structure will be seen. Thus the system of Portuguese expansion for Henry the navigator contained elements such as vessels and their masters. A shift in focus from Henry to the master and his vessel would bring a further network of sailors, spars, and stores into focus—a network with its own force that, when placed within the system of Portuguese expansion, acted as a single unit. If the vessel and its master did not play the roles defined for them in the network of expansion, then the elements that make them up might, of course, have become individually relevant in Lisbon and been built into Henry's expansion network. Such adjustment is consistent with, and indeed exemplifies, the original proposition that the extent of a network is defined by the presence of actors that are able to make their presence individually felt.[13]

This also means, of course, that the heterogeneous engineer standing at the heart of his or her network is not in principle analytically privileged. It is true that, for the purpose of the particular study, I have chosen to follow one system-building effort—that of the Portuguese maritime planners. I have done this in order to set practical limits to the analysis. In making this decision, however, I have not committed myself to the notion that system builders are primitive entities that are themselves unamenable to analysis. Just as vessels or navigators are fashioned out of the interaction between networks of forces, so too are heterogeneous engineers. Indeed, the fact that these are in a position to build systems is itself the outcome of a set of interactions among forces of different degrees of obduracy. To put it more simply, the king of Portugal is just as much an effect as a cause: He is the effect of a set of endless transactions that are, in principle, available for analysis. In the present study, I chose, for reasons of simplicity, to treat him as a cause and navigation as an effect, but in another study these roles, or ones like them, might just as easily have been reversed.

In summary, there are thus two closely related methodological principles for the study of heterogeneous networks. The first, that of generalized symmetry, states that the same type of analysis should be made for all components in a system whether these components are human or not. The second, that of reciprocal definition, states that actors are those entities that exert detectable influence on others. Applied to a relatively stable system, we can therefore define the extent of that system or network by the range of actors that operate as unitary forces to influence the structure of the network. In this chapter I have attempted to follow these two principles in an analysis of the Portuguese expansion. In reinterpreting the notions of system, adaptation, and technological testing for a historical case, I hope that I have succeeded in showing the relevance of the approach to the analysis of technological innovation.

Notes

I would like to thank Serge Bauin, Wiebe Bijker, Michel Callon, David Edge, Rich Feeley, Elihu Gerson, Antoine Hennion, Tom Hughes, Bruno Latour, Jean Lave, Mike Lynch, Chandra Mukerji, Trevor Pinch, Arie Rip, and Leigh Star, who all read and commented on earlier versions of this paper. I would also like to thank the University of Keele, l'Ecole Nationale Superieure des Mines de Paris, la Fondation Fyssen, the CNRS, and the Leverhulme Foundation for support and study leave. Finally, I am grateful to the librarian of the University of Keele for kind permission to reprint illustrations from sixteenth-century works held in the Turner Collection of mathematical texts at the University Library.

1. It is fully described by Pinch and Bijker (1984 and this volume). See also Bijker (this volume).

2. I am not suggesting that these authors all use a social constructivist approach but that their material is susceptible to an analysis in those terms.

3. For another study using a systems approach, see MacKenzie (this volume).

4. Pinch and Bijker (this volume) talk of the effects of advertising on the formation of social groups.

5. Although I have made reference to the work of Hughes, the same point can, I believe, be made in reference to Constant. His notion of coevolution (1978) also

seems to represent an attempt to grapple with the interrelatedness of heterogeneous elements and to handle the finding that the social as well as the technical is being constructed. In addition, the analysis of the development of traditions of "technological testability" developed by Constant (1983) can be seen as a study of the way in which a wide range of actors comes to a locally enforceable agreement that certain social/technical relations are appropriate and workable.

6. Arguably we are *all* heterogeneous engineers, combining, as we do, disparate elements into the "going concern" of our daily lives. In the present essay I am concerned, however, only with large-scale, technologically relevant system building.

7. As I have indicated, this approach parallels that of Callon. It also, however, owes much to the work of Latour (1984).

8. What follows is an example of what I call rational reconstruction. See the conclusion of this chapter.

9. The portolano or plain (that is, plane) chart was laid out using wind roses and rhumb lines of constant magnetic bearing.

10. In what follows I have been highly selective with respect to material in order to highlight what I take to be the essentials of the process and to avoid getting bogged down in detail. For similar reasons I have also taken the liberty of reorganizing the chronology of events by talking of the establishment of the latitudes of important points on the coast after discussing the *Regimento*. For a fuller sociological account, see Law (1986a).

11. Similar arguments have been made by Woolgar (1981), Yearley (1982), and Gallon and Law (1982).

12. Having said this, however, I willingly concede that in the present chapter I have sometimes been obliged, because of lack of data on medieval and early modern maritime practices, to make use of a kind of "rational reconstruction" in order to show how nature and society affected the Portuguese analysis of their problems. It should be understood that I use rational reconstruction not for the purpose of epistemological judgment but to try, matter of factly, to work out what appears to have happened in cases in which historical data is lacking. For a more extended discussion of rational reconstruction and inadequacies of data, see Law (1985). It is obvious that this procedure is less than ideal, but unless whole empirical areas are to be denied to us, it is obviously unavoidable.

13. It is clear from what has been said that any network stands at the intersection and (if it is relatively stable) profits from the force contributed by endless other networks that have been simplified into individual units. See Callon (1981a) and Law (1984b).