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ABSTRACT This paper documents the connection between the technological and political transformations of late 18th-century France. Its subject is the efforts of state military engineers to produce functionally identical artifacts (interchangeable parts manufacturing). These efforts faced resistance from artisans and merchants attached to the corporate-absolutist *ancien régime*, for whom artifacts were idiosyncratic, and 'thick' with multiple meanings. I argue that to oblige artisans to produce standardized artifacts, the military engineers defined these artifacts with instruments such as technical drawing and the tools of manufacturing tolerance, which the engineers then refined in increasingly rule-bound ways to forestall further subversion by artisans. Hence, I offer a historical account of how the 'objectivity' of these artifacts was the outcome of social conflict and negotiation over the terms of an exchange. In particular, I explain why engineers eventually turned to projective drawings (including the descriptive geometry) over alternative ways of representing artifacts (such as free-hand, academic, and perspectival drawings). And I document the origins of manufacturing tolerance, in which the dimensions of an artifact were circumscribed with gauges and machine-tools to preclude possible sources of disagreement. The paper closes with its own 'thick' narrative of how standards of production emerged out of social conflict in a particular community on the eve of the French Revolution – a process which reflected the emerging political 'toleration' of the French state for its citizen-producers. The SCOT programme can be used to provide a political account of how the operation of seemingly 'objective' artifacts can be coordinated across vast physical, temporal and cultural boundaries.

Making Things the Same:

Representation, Tolerance and the End of the *Ancien Régime* in France

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We live today in a world of mechanical clones: identical artifacts composed of identical parts. When a piece breaks in our bicycle, our automobile, or our computer, we don't throw the whole machine out; we replace the broken piece with a piece which is functionally identical. What makes possible this world of identical artifacts? A world in which 10,000 bicycle gears cut in Japan can be shipped halfway around the world to Mexico and fastened successfully to 10,000 hubs? How did such a world of uniformity come into being? And what does its emergence suggest about the way we should conceptualize technological change?

The usual response to these questions about the origin of interchangeable parts is to point to the advent of Fordist mass production in the

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early 20th century, a period associated with the consolidation of corporate capitalism and the Second Industrial Revolution. Fordism is a form of production predicated on a logic of achieving low unit costs by eliminating the need for skilled labour in the shaping and fitting of pieces. But historians have shown that it was not industrial capitalists, but state military engineers, who first conceived of the ideal of uniform production – and who partially realized it – one hundred years before Henry Ford, back in the late 18th century. This was a period associated with the First Industrial Revolution, and also with the political revolutions in France and America.[1] I will suggest that this earlier timing is no accident. I examine the origins of the ideal and practice of 'making things the same', to demonstrate the intimate relationship between the political and material revolutions of the late 18th century.

Understanding how artifacts were made identical, however, will mean paying attention not only to new 18th-century ways of making things, but also to new 18th-century ways of representing them. In particular, the making of identical parts required new forms of technological representation capable of coordinating the efforts of diverse people with divergent interests. Long before the advent of the computer, material artifacts were being produced in conjunction with techniques and representations ('information technologies') that were themselves subject to a process of standardization. As we will see, these forms of technological representation – mechanical drawing and manufacturing tolerance – had the property of rendering artifacts with a new degree of 'objectivity'; but that is not to say that these representations were politically neutral. On the contrary, the form taken by the new representations was part of the new enlightened political order inaugurated in the 18th century. In our own day, computer-aided manufacturing is radically altering the representations and practices which govern late 20th-century production. The designs of engineers are now being realized with hitherto unsurpassed exactitude. Yet as Shoshana Zuboff and others have noted, the process by which these idealized designs are realized is transforming power relations in the workplace, breaking down traditional hierarchies in some places, reinforcing them in others.[2]

For similar reasons, the story of the *origins* of 'making things the same' poses a challenge and an opportunity for the programme in the social construction of technology (SCOT). SCOT has been the ascendant approach to the history of technology for the last 15 years – and for good reason. SCOT has taught students of technology several essential lessons: to pay close attention to the internal workings of artifacts; to value empirical historical analysis; to study the divergent meanings that different groups ascribe to the 'same' technology ('flexible interpretation'); and finally to ascribe the triumph or failure of any particular technology to the clout of its sponsors, rather than the inherent properties of the technology itself (the principle of 'symmetry').[3] If anything, these lessons have been insufficiently recognized outside the discipline of technology studies. Many cultural critics still try to address the 'social life of things' solely in terms of production and markets, without taking into account the role of technological design and designers.[4]

Yet the SCOT programme, as widely practised, has several limitations worth addressing. One complaint is that SCOT has generally ignored the problem of production.[5] Another concern is that those versions of SCOT which can be reduced to 'interest theory' have sometimes collapsed into a form of local social determinism, and have thereby failed to grapple effectively with some important issues in the relationship between technology and society. In particular, these localized studies do not account fully for the ways in which artifacts seem to possess a kind of innate potency, on the one hand, and how they carry social and political values across temporal, geographic and cultural boundaries, on the other. This is not a trivial concern. Technologies travel across boundaries, sometimes with devastating results. And over the course of the past two centuries, bureaucracies have emerged capable of coordinating the operation of these technologies in diverse environments. Understanding the process by which artifacts come to transcend the local conditions in which they are conceived and produced should be one of the central tasks facing any satisfactory approach to technology. In particular, to ignore the potency of 'travelling technologies' in the case of modern weaponry would be morally unconscionable.[6] Historians need a genuinely historicist way to conceptualize the process by which artifacts are shaped by local interests, and yet are also made capable of being coordinated across vast distances. Doing so will not prove that these sorts of artifacts cease to bear political values; on the contrary, it will show that they bear the political value called 'objectivity' which is characteristic of modern technological systems.

In this paper I seek to develop such a methodology and frame it within a general historical problem. The historical question I will address is the perplexing relationship between the two profound political and economic revolutions which transformed much of Western Europe in the late 18th century. The political transformation led from absolutism to popular sovereignty, and achieved its moment of highest visibility during the French Revolution. The economic transformation led from the guild system of production to entrepreneurial capitalism, and has generally been studied under the rubric of the Industrial Revolution. Of course, neither transformation was fully accomplished within the compass of the late 18th or early 19th century, nor was the pattern of change the same in all European countries, nor even in all regions of those countries. Indeed, 20 years of historical scholarship have emphasized the unevenness and diversity of both of these political and economic revolutions. Still, their conjunction in the later 18th century has been widely understood as marking the boundary between the early modern and the modern period, even if the nature of this conjunction has long been a matter of controversy, especially for those historians who concentrate on France.[7]

In that country, the political transformation led from an *ancien régime* polity (in which an absolutist sovereign legitimated all roles and recognized no realm of private action) to the emergent system of modern politics, proclaimed in the early days of the French Revolution, in which sovereignty flowed from the people, and which assumed a clear separation between public and private spheres. In the corporatist régime of pre-Revolutionary France, the king accorded distinct legal status to different sorts of subjects (nobles, commoners, city-dwellers, peasants and so on) on the juridical assumption that these groups had agreed to alienate their natural liberties to the sovereign in return for a set of privileges and obligations that were particular to them. On these grounds, the king denied political status to members of religious minorities, and justified the different kinds of justice rendered to different sorts of persons. In practice, this legal particularism had been eroded by the monarchy's bureaucratic interest in centralizing authority over the military, taxation and justice. But local interests still prevailed in many instances, and the king still governed by personal authority.[8]

Against this *ancien régime* of dynastic interest and private law, we may set the modern polity based on national citizenship and public law. Crucial to the vision of the 'enlightened' nation-state which energized French reformers in this period was the ideal of toleration. This ideal was supposed to govern the relationship among citizens, and between citizens and the state, by carving out a realm of private conscience and public speech, and by punishing (in theory) only those actions which brought harm to others or to the public good. The demand for toleration – particularly for religious toleration – was one of the principal battle cries – perhaps *the* principal battle cry – of the Enlightenment. One need only think here of the assertions of John Locke and Pierre Bayle at the end of the 17th century, or the declarations of Immanuel Kant or Voltaire in the middle of the 18th century. To be sure, the seeds of political toleration, sown in the *ancien régime*, were only fitfully realized in the course of the 19th and 20th centuries. But in theory, at least, the boundary between the private and public spheres was henceforth to be defined by a forever-elaborated set of public laws. It is important to emphasize, however, that these Enlightened reformers did not believe that the ideal of toleration meant that the state should absent itself from public life, nor that the populace should directly mete out justice. On the contrary, what Voltaire feared was both the tyranny of the despotic state (which operated according to a system of private and secret justice) and intolerance of the mob (which acted without reason). In this enlightened vision of toleration, the state was expected to play a crucial role as the guarantor and regulator of the public order.[9]

In this paper, I argue that this hope for political transformation was crucial to the concurrent transformation in the representation and making of identical goods.

From 'Thick Things' to 'Objective Objects'

The methodology I will use to develop this argument will consider artifacts as the outcome of a history of exchanges in which parties with distinct interests negotiate their differences. The technology which results from this process, I will argue, is both the bearer of political values *and* can in some sense be called 'objective'. In recent years, a group of scholars have made various attempts to define more carefully what they mean by the 'objectivity' of techno-scientific results. They have distinguished carefully between the claim that objectivity means the 'truth' about nature or some matter of public concern, and the more limited claim that objectivity denotes something akin to 'impersonality' or 'disinterestedness'. In what follows, I take my cue from this literature, applying to artifacts the same sort of analysis with which Theodore Porter has tackled the problem of quantification.[10]

Porter argues that the reduction of a natural phenomenon or some facet of public life to a numerical result does not simply reflect the underlying truth about the subject (though it may do that in part), but also represents the outcome of a process of conflict between mistrustful parties. Experts who resort to numbers generally do so because they find the stability of numbers a valuable tool for managing complex and far-flung operations. But it is only under pressure from powerful outside forces that they agree to make their numbers public. After all, experts understand that the full and public articulation of their rules of calculation restricts their ability to make flexible judgements in the face of changing circumstances. This public articulation, moreover, reduces their private discretion about these matters, and hence, their personal power. What Porter and others call 'mechanical objectivity' is the kind of description of nature (or society) which experts provide when they wish to present their conclusions as having been derived with a minimum of human intervention. At the limit, these results are conveyed as if by machine, and mask a different sort of power which operates under the guise of impersonality. This form of objectivity is part and parcel of the contractual relations endemic to modern, mistrustful polities.

Over the past 200 years, many of the artifacts of commerce and industry have come to acquire a similar degree of impersonality. This was not a trivial achievement. The material world is lumpy, recalcitrant and inconsistent. Connections come apart; parts wear out; things break. Those people who work with material objects – let us call them 'technologists' – find it challenging enough to manipulate physical matter so as to build a single artifact which works in the prescribed manner in the workshop, let alone consistently repeat this set of manipulations several thousand times over and still ensure that these artifacts function effectively in a diverse set of environments. In short, things are 'thick'.

By the phrase 'thick things', I mean to invoke two aspects of material artifacts. First, the difficulty of consistently shaping the material world into a working artifact, or what one early modern technologist called the 'resistance and obstinacy of matter'.[11] And second, the related challenge of assimilating ordinary artifacts to any idealized representation in such a way that their qualities can be captured in their entirety. Here I borrow the term 'thick' from Clifford Geertz, who urged anthropologists to provide 'thick descriptions' if they wished to capture the diverse layers of meaning with which different human agents imbued their actions and those of their fellows. Geertz contrasted the capacity of thick ethnography to represent multiple (and often divergent) human points of view with the reductive 'thin' descriptions in which scientistic anthropologists collapsed actions into a simplified matrix of behaviour or function.[12]

For my purposes, the thickness of both artifacts and their representations can be contrasted with the 'thinning' process by which scientific objects are often made amenable to analysis. Here, Gaston Bachelard provides a valuable hint. He notes that the synthesizing power of explanation in the physical sciences depends on a vast array of precision scientific instruments which investigators wield in order to create objects that are mathematically tractable, and can therefore constitute legitimate objects of inquiry. In the extreme case of 20th-century physics, these objects (electrons, for instance) become more than similar: they become ontologically identical; and this in some sense accounts for the fact that their properties can be described with unsurpassed precision and economy.[13]

The ordinary material artifacts of everyday commerce are not, of course, readily amenable to this exacting form of representation, nor this extreme degree of regimentation. But, as we will see, some technologists have been driven to assimilate artifacts to this sort of analysis, and – not coincidentally – to embed them in technological systems. Making things the same, and ensuring their success in diverse environments, requires the coordination of many diverse people – whether by cooperation or by coercion. And common forms of representing artifacts proved essential to this endeavour.[14] The manner in which these representations were achieved, however, did not involve a one-sided imposition of standards by some technologists upon others, but emerged as part of a wider process of social struggle and negotiation. Indeed, I will argue in this paper that it is the pressure of social conflict which has, over time, obliged technologists to define explicit rules for their representation of artifacts. In particular, to guarantee that these artifacts could be defined with 'mechanical objectivity', these technologists have been obliged to embed these rules in general 'instruments' capable of defining, comparing and judging all manner of artifacts. Two instruments – mechanical drawing and the tools of manufacturing tolerance – were developed by engineer-technologists during the Enlightenment, and were further refined by them in response to outside pressures. In the hands of these engineers, mechanical drawing went from being a pictorial representation of the artifact, to a rigorous ('thin') definition of its physical form. The tools of manufacturing tolerance included gauges, jigs, fixtures and even automatic machinery, all deployed by engineers to define and shape artifacts in new and more precise ways. The invention and construction of these tools was, of course, the work of individual technologists – but the way that these tools were actually configured in the workplace was inevitably a matter of wider social negotiation. When coupled with the new scales of measurement introduced in this period (such as the metric system), these instruments have been essential in enabling technologies to travel across physical and cultural boundaries. In this sense, they are akin to those semiotic devices that Bruno Latour has called 'immutable mobiles'.[15] As we will see, however, such mobiles are themselves the outcome of a social struggle over how to conceive of and enforce standards of production.

Conceptualizing technology in this way has several advantages. First, rather than view technology (including the means of its production) as simply an external resource which generates social conflict, it understands technology (including the means of its production) as the *outcome* of ongoing social conflict and negotiation, as well as a source of further conflict. Second, this approach thereby folds the making of technology (including the means of its production) back into the historical process without prejudging the relative strength of the parties to these conflicts and negotiations. Third, it thereby allows human agents and contingent factors to set the pace and direction of technological change – even as it points to a shift in the terrain upon which such conflicts and negotiations took place in the 18th century. And fourth, it draws our attention toward the factors which made possible the rise of modern technological systems out of the demise of the corporate order of the *ancien régime*, and the crucial importance of information technologies in that transition.

In the remainder of this paper, I will proceed as follows. First, I describe the structure of the corporate order – and the agenda of its opponents among the *philosophes* and state engineers. Second, I lay out the *logic* behind the two instruments – mechanical drawing and manufacturing tolerance – which these engineers developed in order to tame artifacts and their makers. Third, I provide my own thick description: a detailed case example of how identical artifacts and the instruments which made them possible emerged as the negotiated response to social conflict among parties with diverse understandings of artifacts – and can thus be understood as the outcome of a *historical* (rather than a logical) process. And fourth, I conclude with some general remarks on the relationship between the modern French state and capitalism, and the political and technological revolutions of the late 18th century more generally.

Replacing the Corporate Order

Social and economic historians have long wondered how and why production in Western Europe shifted from the artisanal workshop to the entrepreneurial factory. The approach of economic historians, such as David Landes or Joel Mokyr, is to couple the rise of factory organization with technological creativity motivated by the heady lure of profits.[16] In complementary fashion, business historians such as Alfred Chandler have emphasized the essential role of the entrepreneur-manager as the organizer of production.[17] And advocates of the 'proto-industrialization' thesis have suggested how capitalists first gathered outworkers from rural areas under a single roof in a transitional Age of Manufactures.[18] Each of these schemes (there are others, of course) has illuminated different aspects of this great transition. Yet all spin some kind of teleological narrative. As recent commentators have noted – William Reddy, Tessie Liu and Maxine Berg among them – each assumes the success of the phenomenon it seeks to explain: the rise of machine production, the emergence of the entrepreneurial role, or the triumph of capitalists over domestic producers.[19] Up to a point, this form of teleology is salutary because it focuses the historical attention. However, as Charles Sabel and Jonathan Zeitlin point out, teleological histories of industrialization have obscured important aspects of that process, such as the continued vitality of small-scale flexible production well into the supposed heyday of mass production.[20] A genuinely historical point of departure, then, is to ask how 18th-century élites tried to manage the transition away from artisanal production, and how 'rational production' emerged from the *resistance* these schemes encountered.

The artisanal guilds which controlled craft production in the *ancien régime* participated in the corporate order whose legitimacy rested on the theory of absolutism. That is, the members of each of the various mercantile and productive associations had collectively surrendered (alienated) their natural liberties to the sovereign in return for the privilege of organizing their own affairs and exercising a legal monopoly over a particular portion of trade. As William Sewell has noted, these collectivities validated this monopoly around a notion of 'art', a set of tacit and unspecifiable skills which could only be acquired through a long apprenticeship in the trade, and which governed the norms of their social life.[21] And as Michael Sonenscher has pointed out, these artisans considered themselves to have a natural property right in their own labour power – and this included not only those master artisans who sold goods in the marketplace, but even those artisans and journeymen who worked in large workshops and under an extensive division of labour.[22] For these artisans, the price of their alienation of this labour right was the wage, whether it was paid for a day's work or for the making of a particular article (the *prix de façon*). This legal fiction of the ownership-wage is what distinguished the artisan from the slave and dependent servant, and it had real implications for the ability of workers to make claims about the proper division of labour in the workshop, the amount of time they spent on set-up work, and their customary rights to the by-products of their labour. Craftwork, then, was not simply a mode of hand-made production (artisans can use machines too), but a social, cultural, and legal system which validated collective privileges and individual property in skill.[23]

This was part of a larger pattern of legal entitlements which governed not only the production of artifacts in the *ancien régime*, but also their sale, purchase and use. Not only did guilds superintend the distribution and retailing of most consumer goods, but their consumption, too, might be limited to particular classes of persons, either by formal sumptuary laws or by customary codes. Even the measurement of goods was particular, in that individual guilds used their own units of measures, and these generally differed from one local jurisdiction to the next. Under the theory of absolutism, therefore, to forge a musket barrel, to concoct a new sort of soup, to sell a bolt of linen or even to wear a certain sort of hat, was in some sense a legal privilege. In such a scheme, every artifact was not simply individually 'custom-made', but was understood to be idiosyncratic, personal, and particular.[24]

However, a growing number of 18th-century élites – many of them associated with the Physiocratic movement of the French Enlightenment – were convinced that the corporate system of production was deficient. As a practical matter, the monopolies of the various guilds had been eroded by the expansion of rural manufactures not covered by the statutes. But only during the Enlightenment did the corporate system come under explicit political attack. In the last decades of the *ancien régime*, the Physiocrats and their allies began to argue that the guilds, by zealously guarding technical knowledge in private hands, had restricted innovation, artificially raised prices and involved the state in endless litigation. When one of their allies, Turgot, became chief minister in 1775, he banned the corporations. Although the guilds were revived shortly thereafter, the Revolution abolished them permanently in 1791. It is worth noting, however, that although Turgot was an advocate of 'laissez-faire', he expected that the state would continue to play an active role in guaranteeing standards of production and in regulating trade. In other words, these French reformers did not advocate the market principle of unregulated private exchange, but the ideal of the market-*place* where transactions between parties could be guaranteed by the state.[25]

The question for these élites was: what was to replace the guilds? For all their hostility to the corporate system, these *savants* recognized that the corporations formed a coherent world which organized the social life of artisanal producers, as well as daily practices in the workplace. In the absence of the corporations, who would decide how to set up work schedules, and how? What would the rates of compensation be? The answers to such questions had important implications for the distribution of wealth and knowledge in society. Yet these theoreticians of the workplace did not necessarily anticipate the outcome that leaps to our lips today: 'the machine', 'the entrepreneur', 'the market'. What they called for was the creation of a new kind of *public* technical knowledge.

This programme for a public technological knowledge was most fully developed in Diderot's famous article, 'Art'. There, the cutler's son made a plea for the mutual aid that the *savant* and craftsworker should offer one another. Theoretical training was counterproductive unless combined with a practical knowledge of basic physical properties. In the same breath, however, Diderot showed his appreciation of the organizing power of theoretical science by calling for a 'Logician' to invent a 'grammar of the arts'. He deplored the secrecy and venality of the various guilds, which he felt stifled technical innovation. One sign of this secrecy was the chaotic terminology of the trades. The first task of Diderot's Logician, therefore, would be to devise a quantitative scale to express the various measures of tools (their size, force of action, *et cetera*) and to initiate a morphological analysis of their shape by means of technical drawing – or what he called 'the geometry of the workshop'. Where once the tacit and personal 'art' of the guilds had organized production (thereby stifling the free exchange of both goods and knowledge), henceforth an open and public 'science' – conducted by means of rigorous analysis – would generate innovative technical knowledge. The *Encyclopédie* was itself to be the first instalment of this programme.[26]

Diderot's praise for the ideal of open science, and his denunciation of proprietary rights to technological knowledge, was part of the *philosophe*'s larger critique of the *ancien régime*'s world of private justice, personal offices, and privileged status.[27] What was new in the 18th century was the concurrent effort of the French state deliberately to close this gap between science and technology. The French engineers were trained to just this end.

Enlightenment Engineering and the World of Production

The military engineers of the 18th century mediated between the French state and the world of commerce. Trained by the state in the first formal techno-scientific schools in Europe, they were enjoined to partake of neither the routine and secret practices of the artisanal corporations, nor the abstract and purposeless speculations of the *savant*. Instead, these engineers were to combine theory and practice in a programme of institutionalized innovation. Their school curriculum focused on mechanical drawing, rational mechanics and the practical details of their trade. This cognitive programme was meant to carry particular social lessons: engineers were not to be venal and collusive like the artisans, nor aloof and asocial like the *savant*. Instead, they were to vie in meritocratic competition (an identity consonant with their dignity as notables), even as they acquired an ethos of hierarchy and subordination. They were to be both technically competent and loyal servants of the state. In short, they were to be professionals.[28]

At the beginning of the 18th century, the military engineers of the artillery service became the sole intermediary through which the army acquired all its weaponry: cannon, artillery carriages, munitions and small arms (muskets, pistols and sabres). No longer would colonels supply their own troops with weapons. This was part of the absolutist state's effort to make the army answerable to a central command. Yet France, like other states of early modern Europe, did not thereby assume ownership of the means of military production. The military market may have been large and undifferentiated, but it was erratic. Consequently, the state allowed merchants and artisanal producers to absorb the risks associated with these investments, while cloaking these producers in legal privileges and assuring them lucrative (if intermittent) profits. And to make sure that these provincial producers and traders delivered the agreed-upon goods at the agreed-upon price and with some assurance of quality, the state sent artillery-engineers known as 'inspectors' into the provincial armouries.[29]

These artillery-inspectors were enjoined to see that the army's guns were made more precise and uniform, to make their operation more reliable, accurate and deadly. Precision and uniformity are here to be understood as mirror-image twins. Precision, as measured against a background uniformity, ensured that a single weapon behaved the same over time. And uniformity, as measured with precision, ensured that numerous weapons behaved similarly to one another. From the point of view of the army, both attributes promised to make the infantry drill more effective. From the point of view of artillery service, both attributes also allowed them to police their monopoly over this prestigious piece of the *ancien régime*'s military-industrial complex. In particular, by setting rigorous standards for production, the engineers ensured that interloping colonels and merchants would be unable to strike private deals for weapons, and that all weapons would have to be procured through them.

But how were these rigorous standards to be enforced? In the first half of the 18th century, the artillery-engineers had supervised the armouries through the same mechanisms of privilege which the monarch used to regulate the trade corporations. Only certain designated artisan-armourers could produce guns for the king and, as a mark of their privilege, they received tax breaks and other local legal advantages (exemption from militia service, the obligation to house soldiers and submit to the *corvée*, and so on). In return, these artisans were obliged to sell their wares at the stipulated price exclusively to certain merchants (known as 'Entrepreneurs'), who were legally designated as the sole buyers of arms for the king, and who also enjoyed an array of fiscal privileges. In theory, these provisions were backed up by the threat of martial punishment, and the armourers were nominally subject to military law. But armourers and merchants were not always eager to comply with the quality and cost requirements set by the artillerists, and they disagreed among themselves about how to divide the tasks and profits of gun-making. Forced to sell at fixed prices, they cut corners on quality or attempted to leave the king's service. Already in the 18th century, some 20 different subspecialists contributed to the making of a gun, and each of these artisans considered himself to possess a right in the product of his labour. Moreover, all these artisans and merchants had a real opportunity to make good on this claim by shifting their skills and capital to the private market for guns which existed right alongside the royal armoury.

So, in the middle of the 18th century – under the reform-minded leadership of First Inspector-General Jean-Baptiste de Gribeauval – the artillery inspectors adopted a new managerial role *vis-à-vis* the armourers. They sidelined the Entrepreneur's role as the coordinator of production, and began to set the price for individual gun parts themselves, rather than just for the final finished product. But this meant that the engineers had to define detailed standards for each individual gun part, rather than simply asking for assembled, functional guns. But how were the engineers to enforce these new standards, to superintend the fractious provincial manufactures? One of their solutions was to adapt new kinds of technical drawings.

Drawing Things the Same

In recent years, a number of scholars have turned their attention to the representation of techno-scientific objects. Many of these studies have sought to uncover the ways in which representations have underpinned the 'objectivity' of scientific results. Lorraine Daston and Peter Galison have studied illustrations in scientific atlases, noting that they signal an effort to suppress individual and group idiosyncrasies, and thereby (supposedly) obviate any need for interpretive judgement. Their approach highlights the moral act of abnegation and self-discipline which these practitioners sought to associate with scientific investigation.[30] Michael Lynch has noted how scientists use certain kinds of representations to perform a 'disciplining of the object': a process by which the graphical properties of the object are made to embody the 'natural object', making the object scientifically knowable and manipulable, much like the docile bodies of Foucault's prison institutions.[31] This approach implicitly reminds us of the difficulty of ever fully capturing in two dimensions the variety and intractability of 'thick' things. More generally still, Bruno Latour has referred to these 'rationalist' forms of representation as 'immutable mobiles'. Latour argues that images in this guise can be transported across physical and cultural distances without undue distortion, and collected at a remote site of power. There, at these 'centres of calculation', these images can be analyzed and synoptically compared with other images, so that discrepancies may be noted and corrective actions taken. To the extent that a cathedral plan coordinates stone-cutters and a military map deploys soldiers, an engineering drawing commands workers. Of course, pictures do not in themselves coordinate, deploy or command. These drawings make possible the exercise of power by enabling their possessors to master phenomena on a scale inaccessible to others.[32]

Each of these scholars identifies crucial aspects of scientific representations. However, each slights several important features of the new forms which these representations took in the 18th century, at least as they were deployed in the workplace and in the management of practical affairs. These authors do not pay sufficient attention to the *alternative* ways of representing objects that were available to contemporaries. Eighteenth-century engineers, for instance, came to prefer projective representations, whereas natural philosophers used perspectival views, and artisans were taught freehand drawing. This omission is serious because these authors do not show how these different forms of representation emerged within the context of different social milieus, and hence implied very different sorts of social relations between image-makers and object-makers. The differences in these sorts of social relations, I would argue, are what made the choice of any particular form of representation so contentious. And this omission means that these authors also cannot give a historical account of *why* particular types of these drawings emerged in this period as the dominant way to represent artifacts, at least for the management of technical affairs. Finally, all these authors fail to acknowledge the severe limitations on *any* attempt to master the physical world solely by means of visual representations. Our analyses of representations – at least as they related to activities (like engineering or architecture) which are engaged in manipulating the material world – cannot remain stuck in the two-dimensional world of images, but must follow the efforts of engineers to translate their images into physical objects, typically through their use of mediating physical instruments.

Many 18th-century theoreticians of the workplace agreed that one of the principal tools for organizing the workshop was technical drawing. As I noted earlier, Diderot's plea for a public 'science' of technology culminated in the call for the development of technical drawing – a 'geometry of the workshop'.[33] Since the *Encyclopédie* was itself to be a public repository of technical knowledge, Diderot devoted considerable effort to the plates which pictured technology. He recruited many contributors and illustrators to do this work, and thereby convey his message about the value of public discussion in achieving technological progress. Most scholars have recently read these plates as revealing Diderot's hostility to the guilds. They point out that the artisans in them are generally portrayed as anonymous labourers, cut off from the boisterous life of the workshop, silently bent at their tasks. The argument here is that reducing the artisans' skill to a set of routine procedures is a sort of intellectual proletarianization.[34] But as John Pannabecker has recently noted, in a project as vast as the *Encyclopédie*, many of Diderot's contributors were artisans themselves, and some found scope to offer very different representations of technical work that gave partial voice to the tacit skills that were at the heart of their craft. And as for the artifacts themselves, they are depicted in a variety of ways, in perspectival views and projective views, as cut-aways and in disassembly, in schematic views and in operation. This reflects the tradition of the Renaissance collections known as 'Theatres of Machines' – which the *Encyclopédie* consciously emulated – as well as Diderot's attempt to reach a larger lay audience.[35]

But when we turn from the collections of pictures found in scientific atlases and the *Encyclopédie* to the sort of technical drawings which were actually taught in technical schools and used in workshops, this diversity of representational forms falls into a clearer pattern. Eighteenth-century France saw the beginning of a vogue for technical education centred on a drawing curriculum. Across the Revolutionary divide and across the divide of social status, drawing education served as the core curriculum in French technical education. We can identify at least three sites where technical drawing was taught, each with its own preferred form of representation: (1) the thousands of workshops where experienced artisans individually taught free-hand drawing techniques to their journeymen; (2) the scores of state-sponsored part-time scholarship schools in which academic drawing masters taught basic geometry and classical drawing to apprentice artisans; and (3) the handful of advanced state engineering schools run by the artillery service, the Corps du Génie, and the Corps des Ponts et

Chaussées, in which mathematics professors taught mechanical drawing, including the descriptive geometry, to engineering students.[36]

As 'instruments' to assist in the organization of the workshop, the different forms of technical drawing taught in these various sites implied (but did not require) very different degrees of discretion for conceivers of artifacts and makers of artifacts, and hence a very different set of social relations between these groups. But technical drawing is more than a barometer of such changes. The very vehemence of the debates over the most appropriate way to represent technical objects suggests that these forms of technical drawing were also considered to be a tool for creating a new productive order.

A sketch or 'free-hand' drawing emphasizes the open-endedness of the design of an artifact – and of the ambiguous roles of its conceiver and maker. The rules of drawing here are ill-defined, even idiosyncratic. This is a quasi-private language, used as an extension of the creative process, or as a kind of private notation to oneself or one's immediate colleagues.[37] Such a drawing implies a high degree of trust between the designer and executor of the object. At the limit, they may be one and the same person. For instance, artisans in the furniture trades used free-hand sketches as a bridge between their tacit knowledge and their manual skills; their drawings did not exhaust or replace their skills. That is because even when they copied patterns from others, or used geometric forms, they still exercised discretion about how to implement their designs.[38] This was the form of drawing Jean-Jacques Rousseau recommended for his imaginary artisan-pupil, Emile. Rousseau instructed Emile to sketch directly from nature, so he might learn to see for himself and learn skills which would allow him to be intellectually and financially independent.[39] This sort of drawing, then, implied the creative and economic autonomy of the artisan as *artiste.*

This differed from the form of drawing taught in the more than 20 part-time drawing schools for artisans established by the French state in the middle of the 18th century. The largest of these, the École Royale Gratuite de Dessin in Paris, exemplifies the contradictory attitudes of élite pedagogues as they set out to teach drawing skills to artisans – and to reform craft practice. This Parisian scholarship school, founded in 1766 by Jean-Jacques Bachelier, trained some 4000 student-apprentices in the two decades before the Revolution. The course began with instruction in elementary geometry. Thereafter, students enrolled in one of three curricula – architecture, figures and animals, or flowers and ornaments – each of which involved tracing some 2300 sequential academic drawings in the neoclassical style. None pictured mechanical devices.[40] Bachelier believed that geometry served as a 'mould for the operations of the mind', and would make artisanal work more 'precise' by teaching students the 'exact knowledge of the dimensions of objects considered under various aspects'. His real enemy here was the artisan's 'ignorant and prejudiced' imagination; only geometry could 'prevent the imagination from flying off, and contain it within the bounds of reason'. The neo-classical style, too, would wean artisans from the wild and ungainly designs of their primitive imagination. Self-discipline in taste correlated with self-discipline in the workshop. Bachelier believed that his school gave the habit of work to young men who otherwise tended to be lazy and disorderly. And he asserted that this discipline had practical results: 'From certainty in work comes promptitude in execution; [and] rapid execution will unleash the industry of the nation by lowering prices'.[41] At the same time, however, Bachelier's course played to the artisan's aspirations for autonomy and pride in his craft. The school was to secure for 'each artisan the ability to execute by himself and without outside help those different works which his particular genius for his art enables him to imagine'. It is no accident that the school's funding came from aristocratic patrons and the leading guilds of Paris. The productive world Bachelier envisaged remained that of the independent handicraft worker governed by the norms of corporatist culture.[42]

Views from Nowhere

The third, and largely triumphant, form of technical drawing – mechanical drawing – was developed in the engineering schools of Enlightenment France and is still taught today in technical schools throughout the world. Mechanical drawing, it is worth emphasizing, itself comes in two basic forms, each associated with different professional milieu. First, there is perspectival drawing developed by rationalist artists in the Renaissance to convey 'realistic' views of figures, landscapes and machinery.[43] Second, there is projective drawing, long used by architects (in profile, plan and elevation) to guide the construction of buildings, and increasingly given mathematical form by technologists interested in designing and constructing a variety of artifacts. Both these forms of representation are rule-based, and both claim to offer a one-to-one correspondence with the material world.[44] And both were taught to engineering students. But the differences between them are important too.

In a sense, projective representations function within engineering culture much the way perspective functions within lay and scientific culture: as a picture of 'the way the world really is'. But this analogy can be misleading. Engineers and architects use projective views because they avoid the distortions of shape that Renaissance artists intentionally introduced into their pictures to give the illusion of depth. As Descartes pointed out, perspective is a deception set aright by the judgement of the mind's 'inner eye'.[45] Perspective drawings are 'views from somewhere' and, hence, still within the realm of the personal (albeit a readily translatable 'personal'). Projective drawings, by contrast, look nothing like the 'real world', yet they introduce no distortions of shape. Such drawings are objective in Lorraine Daston's sense of being aperspectival; they are the negation of subjectivity. First adapted for the fine arts by the Renaissance-mathematician, Albrecht Dürer, they became increasingly appealing to technicians in the 17th century. As Abraham Bosse noted in the latter part of that century, projective views are the equivalent of perspective views seen from infinitely far away – except that they are close up. They are truly 'views from nowhere'.[46]

Projective drawings achieve this effect, in part, by reducing the representation of objects (and their decoding) to a set of formal rules. The goal is to limit the discretion of both the person drawing the plan *and* the person interpreting it. In this sense, we may say that a projective drawing is an objective picture of an artifact, even though it 'looks' nothing like the artifact. A projective drawing binds those who use it to a common vision of the object by overcoming at least three layers of potential misinterpretation. First, a projective drawing bridges the epistemological mistrust that exists between the inner eye and the external world. For those trained in its rules, it allows for a full reconstruction of the pictured object on exactly the same scale as the original. Second, a projective drawing creates a common intra-group conception of an artifact across space and time. This feature made projective drawings particularly useful for those bureaucratic organizations which had to coordinate far-flung activities. And third, a projective drawing helps bridge the chasm of mistrust that lies *between* groups by providing a common referent. This feature made these drawings useful at sites, such as the workplace, where diverse individuals had divergent interests.

All these features made projective drawing a particularly appealing form of representation for the French state engineers of the Enlightenment. In the first half of the 18th century, the drawing professor at the Mézières fortification school, Amédée-François Frézier, admonished his students to reject perspectival drawings as inadequate if they wished to speak to subordinates with a minimum of ambiguity; for these purposes, only projective views would do.[47] Analogous techniques of projective drawing were being taught at the artillery schools in the same period. In the 1740s, the commander of the artillery school at Metz could claim that the importance of drafting for engineering students was so widely recognized as to need no defending. According to Jean-Pierre Du Teil, who directed the Auxonne school when Lieutenant Bonaparte was in residence, mechanical drawing was indispensable to all artillery officers. Under the guidance of a drawing master, students began with drawings of the natural terrain or strongholds from various 'geometric' perspectives. They then moved on to exercises in rendering fortifications, artillery batteries, and civil architecture. And from there they made technical drawings – in elevation and profile – of actual cannons and carriages kept in a special *salle des modèles*. This drawing curriculum showed students how the design of these cannon and carriages conformed to geometric constructions. The leaders of the artillery touted these lessons as providing students – these sons of petty noblemen and bourgeois notables – with a common body of knowledge, a ready means of reconstructing designs while far from the arsenals, and a set of tools with which to direct craftsworkers and manage the complex tasks involved in producing these artifacts (see Figure 1).[48]

These attributes of projective drawings were intensified by the descriptive geometry, a mathematicized method of mechanical drawing formalized

FIGURE 1
Artillery Carriage, Gribeauval System

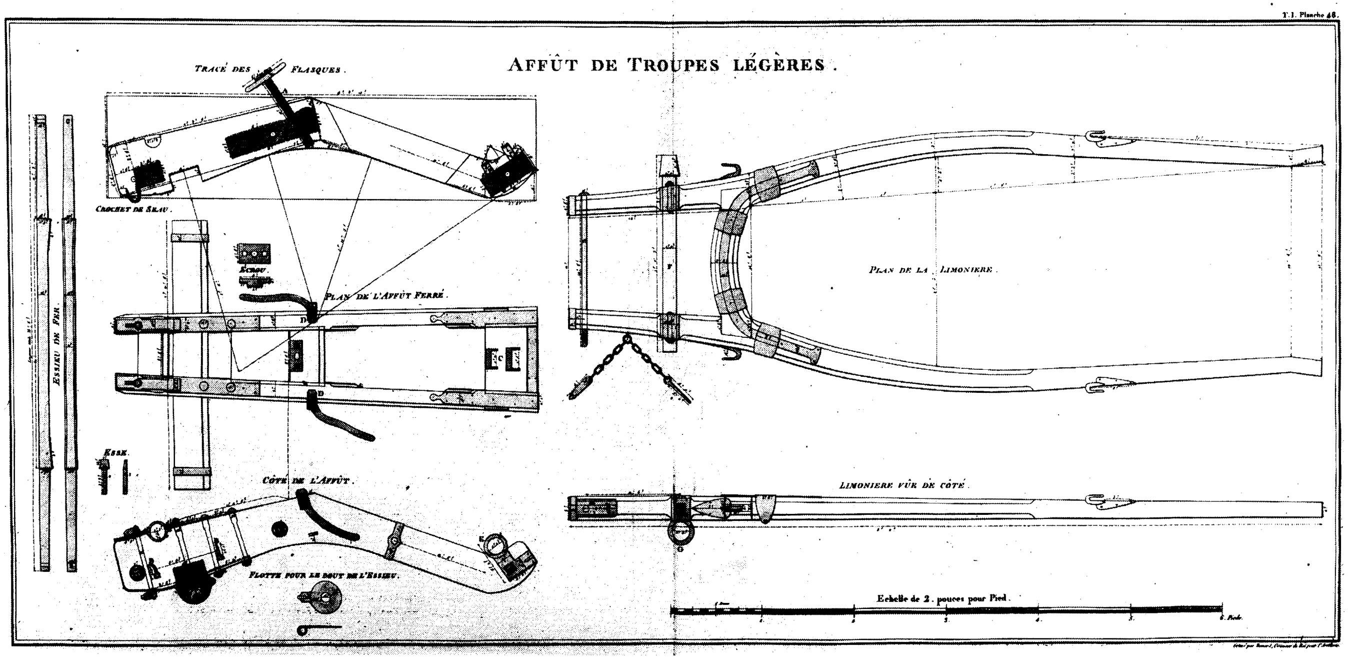


Plate 48 from Gribeauval's *Tables de construction* (1792) provides multiple views of the carriage in rigorously interrelated projective views in plan and elevation. It also shows how one may use geometric 'constructions' to reiterate the complex curved shapes of the carriage. Note the use of shading to make the illustration easier to read.
Source: from the Musée de l'Armée (Paris).

in the 1760s by Gaspard Monge at the Mézières École du Génie, and taught to successive generations of French military engineers. Monge called the descriptive geometry 'a [universal] language necessary to all those who work in the mechanical arts' because it allowed one 'to represent with exactitude, on drawings which have two dimensions, those objects which have three, and which can be rigorously defined'. Certain artisans, such as masons, had long possessed secret stereographic methods for calculating the various block faces needed to build, say, a Gothic vault. These techniques had been generalized by Desargues in the 17th century. Monge's descriptive geometry further extended this generality by referring all representations to universal axes, and by tying these views to mathematical analysis. In particular, it showed how regular three-dimensional objects could be mathematically generated by the movement of two-dimensional lines. As a result, the descriptive geometry was also a powerful 'constructive' technique, and could be used to search for new shapes and configurations. For instance, it helped engineers solve problems in stone-cutting, optimal fortress construction and even machine design.[49]

To be sure, Monge always acknowledged that the descriptive geometry could not be easily applied to the thick things commonly used in commercial and military life. He believed that his limitation, however, only increased the moral value of the descriptive geometry as a tool for training students. As he said:

> [I]f, from a young age designers had been trained in the study of the lines of curvature of different surfaces which are susceptible to exact definition, they would be more aware of the form of those lines and their position, even for objects less [readily] defined; they would [then] grasp them [mentally] with greater precision and their work would be more expressive.[50]

This suggests the central paradox of mechanical drawings: these forms of representation seek to preclude the illustrator's judgement about how to represent an object, but at the same time, one of the central motives for training engineers in this technique is to form their judgement about what are proper objects and how to manipulate them.[51]

Indeed, the very rigour of this training suggests that the descriptive geometry is not a 'natural' representation, but a cultural convention which arose historically and reflects its creators' view of their place in the broader social order. The authority of mechanical representations derives from the *self*-discipline necessary to make one. Before engineers could use pictures of this sort to command workers, the drawings themselves had to be highly ordered entities. Engineering students spent years learning the self-restraint that enabled them to picture only certain carefully defined characteristics of thick objects. In this way, mechanical drafting defined the social role of engineers in late *ancien régime* France as the designers of artifacts, placing them as intermediaries between state patrons and artisans: *vis-à-vis* patrons, projective drawings created a legally enforceable standard which made them accountable to their superiors; *vis-à-vis* workers, projective drawing distinguished between the conception of an artifact and its execution, suggesting how one might redistribute tasks within the workshop, while still preserving a common language for both élite technologists and artisans. These twin aspects of technical drawing – as an analytic method and as a social marker – appealed enormously to the *Encyclopédistes* and contemporary engineers.

Why Do Engineers Cast Shadows?

Of course, for these representations to organize the workplace, they had to be readable by all those involved in production, including those ranked near the bottom of the workshop hierarchy. This explains, for instance, why engineers cast shadows. Strictly speaking, shadows provide no information not already given in the projective views; on rational grounds they are unnecessary. Nevertheless, engineering officers in the *ancien régime* were taught to calculate shadows, since the mastery of this technique was deemed 'necessary to discipline and perfect drawing'. But shadows offered more than an interesting exercise in geometric construction: they also 'rendered representations more distinct'. As engineers recognized, it was often easier to draw an artifact in projective views than to reconstruct it mentally from the multiple drawings. By adding shadows and tints, engineer-writers absorbed some of the difficulty of representation so that patron-readers and worker-readers might more easily interpret their drawings, thereby preserving the correspondence between the hierarchy of expert knowledge and the social hierarchy (see Figures 1, 2, 3, 5 and 6).[52]

The use of these new forms of technical drawing also required an expanded programme of pedagogy for artisans and shop floormen. Thus Antoine-Laurent Lavoisier made technical drawing a centrepiece of his Revolutionary proposals for popular education. He professed deep concern for the growing split between élites 'who studied languages and the objects of science and literature', and those 'destined for the mechanical arts'. To bridge this divide (and still preserve the social hierarchy), Lavoisier emphasized early training in 'graphical geometry' for all youngsters in primary schools.

> Just as there exists knowledge that must be common to all men no matter what profession they are destined for, so must there exist knowledge common to all who work in the mechanical arts. Drawing, it seems to us, must be ranked among this type; drawing is a language of the senses that speaks to the eyes, which gives existence to ideas, and from this point of view, expresses more than words; it is a means of communication between he who conceives or orders [an artifact], and he who executes [it]; finally, considered as a language, it is an instrument proper to perfect ideas; drawing is therefore the first study of those who are destined for the mechanical arts.[53]

Implementing this pedagogical programme became controversial in the Revolutionary period, when some of the conflicts over the early École

Polytechnique became refracted through the question of how much and what kind of technical drawing should be taught to whom. As a founder of the first, egalitarian, and truly 'polytechnic' École Polytechnique, Monge taught the descriptive geometry to his diverse body of engineering students to give them a feel for material objects, practice for their manual skills, and a sense of learning by doing. He and his disciples also tried to see that the technique was taught in the new École Centrales that were to give provincial students access to practical education.[54]

After 1795–96, however, and with gathering force after 1800, technical drawing came to be one of the pedagogical subjects that defined the stratified cognitive order, ranking the state's various educational institutions and the students who graduated from them. While the École Polytechnique was increasingly reserved for wealthy, élite students, and its curriculum refocused on abstract analytical mathematics (including more abstract uses of the descriptive geometry), a range of 'lesser', more practically oriented schools developed in which pupils were taught the forms of technical drawing appropriate to their station. These vocational schools proliferated in the 19th century – including the École des Arts et Métiers and the Conservatoire des Arts et Métiers – and they came to play a crucial role in the dissemination of drawing techniques to the foremen and mechanics who organized production on the workshop floor.[55]

The Limits of Representation: Picturing Guns

Let me emphasize that there is no necessary connection between a particular way of representing an artifact and a corresponding socio-technical order. As Shoshana Zuboff has shown for computerized representations of work, the switch from manually guided machinery to numerical controls did not *impose* a particular form of power relations upon the workplace. In some work sites, the computer representations permitted a blurring of old distinctions between managerial and blue-collar labour. In other sites, they served as a powerful ally for managers who wished to reinforce old hierarchies. The different outcomes depended largely on pre-existing relations between managers and workers, and the willingness of both to countenance new ways of doing things.[56] And as Kathryn Henderson has shown, new forms of computer-aided representation are transforming workplace relations among contemporary engineers, and between engineers and their subordinates.[57]

Similarly, the introduction of new forms of mechanical drawing in the 18th century only made *possible* the separation of the tasks of the conceiver and maker: it did not *require* it. However, by enabling engineers to translate objects into geometric figures, which they could then manipulate and break down analytically, projective drawing enabled engineers to discipline artifacts – and hence to discipline artisans who failed to follow instructions. As Desargues noted in his 17th-century treatise on stone-cutting, his method 'left no shape to chance, or to discovery in the act of making'.[58]

This meant that, in theory, engineers could now define tasks and communicate them with sufficient rigour that the final assembly need not be individually accomplished by a 'fitter'. Mechanical drawing may not have necessitated uniformity in production, but it is hard to imagine organizing production in this way without some such representation.[59]

But when we turn from this idealized disciplinary programme to the way these representations were actually used in the workplace, we see both the authority and the limits of this sort of programme.[60] The French artillery engineers used drawings to define the official French gun design and to discipline their production – yet they encountered serious problems in the practical realization of their idealized designs and drawings. Consider Gribeauval's famous *Tables de construction*, his sumptuous five-volume set of engineering drawings of every component of the artillery *matériel.* These were carefully scaled projective views, with parts specified in dimensions down to 1/200th of an inch. Gauges, jigs and rulers were also represented (see Figure 1). These drawings provided artillery bureaucrats with a common referent for all the objects of their technological life. The pictures gave them an analytical tool for dividing each production job into individual tasks, as well as a disciplinary tool for holding up each piece to an immutable standard. The *Tables* also had the force of law, and served as a sign that the designs were approved by the king – and enforced by his authority.[61]

However, Gribeauval's *Tables* were not published until 1792, even though Gribeauval had proposed his new artillery in 1763, and his designs had been the official French model since 1777. The reasons for this delay are instructive. One might think that the need for military secrecy explains it. But foreign governments generally had easy access to the cannon designs of rival powers in this period, either through spies or by the capture of weapons. And in 1795, when the republic was at war, Gaspard Monge had no hesitancy about publishing his famous *Description de l'art de fabriquer les canons*, along with a set of complete projective drawings of all the French cannon and their means of production (see Figures 2 and 3, overleaf). Apparently, the French state's need to increase cannon production in 1795 meant that disseminating accurate information to provincial French foundry masters outweighed the fear of giving state secrets away. As Gribeauval himself admitted, the real reason the artillery kept its cannon designs unpublished was that formally enshrining them in objective, publicly validated representations would make it difficult for the artillerists to alter their designs as circumstances changed. The public articulation of an artifact's qualities reduces the discretion of the experts. Gribeauval's *Tables* were only published after the Revolution.[62]

In any case, the artillerists had to contend with the fact that no artifact can be reproduced from a two-dimensional drawing alone. No representation can fully capture the set of tacit and bodily skills needed to make a working device. The French engineers learned this when they ordered their workmen to build the idealized drawings of artillery carriages pictured in their *Tables de construction.* In the end, specially trained workers from the

FIGURE 2
Étoile Mobile, Gribeauval System

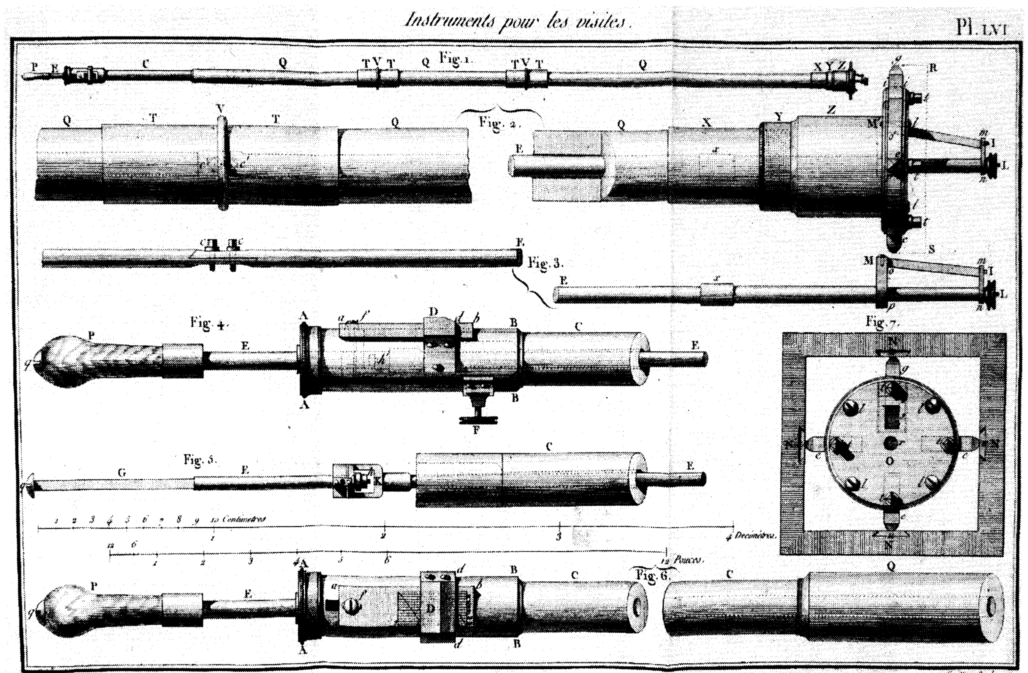


Plate 56 from Monge's *Description de l'art de fabriquer les canons* (1793–94) shows an 'exploded' view of the main precision instrument for measuring the interior diameter of the cannon bore. Note the use of the centimetre scale, which had only that year come into use.

Source: from the Regenstein Library (University of Chicago).

FIGURE 3
Naval Cannon

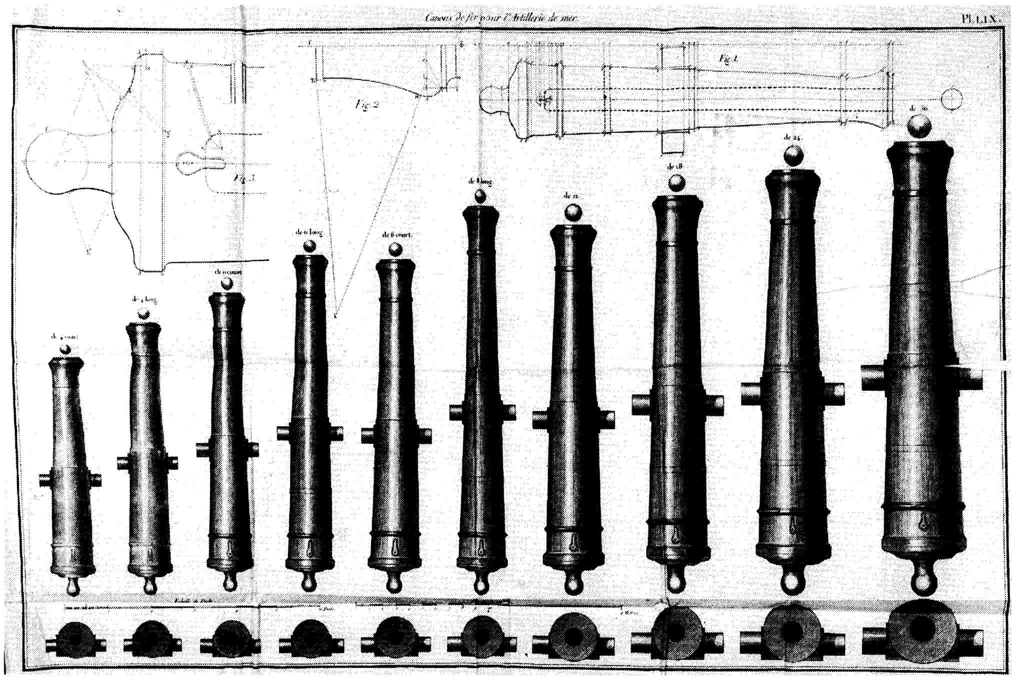


Plate 59 from Monge's *Description de l'art de fabriquer les canons* (1793–94) shows the canon of the navy after they had been subjected to a similar process and rendered uniform. Note the use of the elaborate geometric construction to reproduce the curvaceous breech of the cannon.

Source: from the Regenstein Library (University of Chicago).

Strasbourg arsenal had to be rotated throughout the other arsenals of the kingdom to transmit the tacit skills needed to replicate the carriages.[63] Two-dimensional drawings can never hope to capture fully the boisterous, messy world of thick things.

Mastering Thick Things

Pictures do not, in and of themselves, discipline artifacts or coerce labour. An artisan can make *some* kind of artifact from almost any technical illustration; the question is the degree of judgement exercised in carrying out the 'instructions' embedded in the picture, and the extent to which it matters whether the constructed object conforms to the plan of the conceiver-illustrator. So, to mediate between their drawings and the artifacts they desired, the engineers embodied their instructions in physical 'instruments', among them: gauges, jigs, fixtures, cutters and (most famously) automatic machinery. Go and no-go gauges enable one to judge the 'fit' of some dimension of an artifact against some standard. And jigs, fixtures and cutters guide the shaping of a piece of work, enabling a producer to get a variety of specific actions out of a hand-held tool or a general-purpose machine tool. Yet, despite the centrality of gauges and fixtures to production (both to interchangeable parts production and to flexible specialization production), historians have ignored their contribution to the social history of industrialization. One reason for this silence is that these gauges and fixtures are presumed to be unproblematic agents of social control: disciplinary devices to de-skill workers.[64] But this view presumes that Fordist mass production (in which the gauges and fixtures are built permanently into automatic machinery) is the goal toward which all industrial development aspires. In what follows, I will take the historicist view that gauges and jigs are not some external resource brought in as the imposition of rational producers upon irrational makers. Gauges and jigs – like automatic machinery – are the *outcome*, not the precondition, of conflict in the workplace, though such seeming resolutions are, of course, occasions for further conflict.

To be sure, gauges and jigs *can* be used to stratify the relations between those who conceive of the artifact, those who design the machinery, and those who actually carry out the task. This is because gauges and jigs define the *limits* of the agreement between the parties involved in production. In this sense, they are the physical bearers of manufacturing 'tolerance' – a concept first introduced by the engineers of *ancien régime* France. Everyone in a workshop knows that a manager who demands an ideally fashioned work-piece in fact leaves the worker an unspecified degree of discretion about how precisely to shape it. A specific band of tolerance, however, explicitly spells out the limits of acceptability. And the use of go and no-go gauges (or jigs) defines this band of tolerance in material terms. As for general-purpose machines, they simply take this process one step further by automating the use of the selected fixtures (which can be either altered manually or, in our own day, by digital command). And as for those special-purpose machines with the fixtures permanently installed (as in Fordism), they can then be seen as the final step in the logic of mechanizing, and hence 'objectifying', the standards of production.[65]

But gauges, jigs, fixtures and machines do not, in themselves, entirely eliminate the need for skill and judgement in production. Even though a machine, once it is set up with a jig or fixture, reduces the machine-tender's discretion over how to shape a piece, this does not eliminate the need for expert guidance. Moreover, there is no *a priori* reason why a metalworker cannot set up his or her own machine, nor even forge the gauges, jigs and cutters for him or herself. And finally, the inspector can define tolerances only for a few of the principal axes of the workpiece, and gauges can verify only a small number of these. Moreover, even the act of gauging is itself an art that requires a practised 'touch'. All this means that both the worker and the inspector retain a certain degree of discretion in the verification of the artifact. And this, in turn, means that there is still room for disagreement about whether a piece has been tooled to gauge. The social meaning of gauges and fixtures, then, depends on historically contingent social relations in the workplace.

In the 18th century the use of gauges, fixtures and machinery was hardly novel. The ability to repeat certain tasks and check for deviations had long been of value to craftworkers in their own shop. Eighteenth-century watchmakers and gunsmiths, among many others, made extensive use of mechanical aids, such as calipers and templates. But these gauges and jigs did not necessarily dictate a division of labour in a period when the roles of manager and worker were typically embodied in the single person of the artisan.[66]

Where managers entered the workplace as outsiders, however, as the artillery-inspectors did, these devices did enable the directors of workshops to set standards of production, and thereby separate tasks and shift authority over good workmanship to an impersonal arbiter.[67] Mistrust is a structural feature of the relationship between manager-inspectors and those worker-artisans who consider themselves to have a property right in their labour. Where the worker is on piece-rate wages, or is an independent artisan who bears the cost of rejected parts, inspections can mean the difference between a living wage and starvation. This is where gauges come in handy. They appear to deflect responsibility away from the inspector by referring to a neutral, rule-based standard. Much the same logic operates, according to Porter, in those forms of quantification (accounting practices or cost–benefit analysis) which consist of rules which are arbitrary to some degree, yet nevertheless binding. Such rules are generated at just those points where mistrust reigns, and parties have conflicting interests. Indeed, the elaboration of these rules can be read as a record of the continual attempts to forestall their further subversion. Quantification of this sort is objective in the sense of being impersonal, a set of mechanical operations that seem to preclude independent judgement, and hence the discretion of both parties. Mechanical authority then substitutes for personal rule.[68]

Gauges and jigs play a comparable role in manufacturing. They succeed by appearing to bind workers and inspectors to a common set of impersonal rules at just those points where the possibilities for conflict are greatest. They substitute mechanical authority for personal judgement, and verifiable public standards for trust. This does not mean that conflict comes to an end, however, nor that both parties have equal power in this process. Consider the analogous development in the early modern period of three other sorts of objective measures of work-effort: clock time, payment in specie, and standards of labour effort. E.P. Thompson has described the painful transition from task-time to clock-time in early modern manufactures.[69] This was a protracted struggle, in which workers generally lost much of their ability to control the pace of work. Once workers were obliged to labour by the clock, however, they could verify the elapsed work-time, and even frame an argument about the number of hours they would work in a day: the twelve-hour day, the ten-hour day, the eight-hour day. Peter Linebaugh has uncovered a similar pattern in the bitter transition in English shipyards, as workers there were obliged to accept wage labour in specie instead of in customary payment (in wood chips).[70] In the course of this struggle, artisans lost a proprietary stake in the products (and by-products) of their labour, and thence much of their control over the labour process. But in its place, they now found themselves able to articulate arguments about rates of compensation. And I have written elsewhere about a similar pattern that occurred during the transition from anthropomorphic measures to universal systems of measurement (like the metric system).[71] Whereas the old anthropomorphic measures defined land area, for instance, in terms of the amount of labour needed to harvest it (one *journée* of vinicultural land), and hence set local norms for 'an honest day's labour', the new universal measurement systems could track labour's efficiency against some abstract standard (output per hectare). This enabled workers, however, to stake a claim for some portion of any productivity increase. The emergence of these various sorts of impersonal standards, then, is both an outcome of past conflict – and marks a shift in the terrain of future conflict.

To be sure, the dispute is now fought out on a terrain defined by the supervisor. Gauges, fixtures and machines – like clocks, specie and meter sticks – transform the worker's understanding of his or her own practices into a disembodied quantity whose meaning is only apparent at the highest level of organization. Indeed, the logical extension of this method of defining artifacts objectively is interchangeable parts manufacturing. And in fact, this method of production was first introduced in the 1760s by Gribeauval's artillery engineers for the carriages that carried cannon into battle, and then in the 1780s for the flintlocks of muskets. Under such a production régime, the acceptability of any particular work-piece does not solely depend on whether it passes a gauged inspection – though that may well be the first step – but on whether it fits into the final assembly. Workers are now far less able to complain that their work-piece has been rejected without cause. On the other hand, supervisors may not, in principle anyway, reject pieces arbitrarily. Personal power has been replaced with mechanical authority.

Manufacturing Tolerance: Bores and Balls

To translate this mechanical authority into a mastery over thick things, however, involves more than taking a few simple measurements. It requires engineers to develop a carefully structured hierarchy of standards, which are orchestrated by rigorous rituals of measurement, and given meaning by a committed culture of precision. Consider, for instance, the programme of Gribeauval's artillery-engineers to produce more accurate guns by reducing the 'windage', the all-important measure of the fit of the cannonball into its barrel. Historians have cited the Gribeauvalists' success in halving this parameter as their signal achievement, one which made it possible for them to preserve the accuracy of cannon-fire while shortening, and hence lightening, the cannon. This, in turn, is said to have made possible the mobile wars of the Revolutionary and Napoleonic period. Historians have ascribed this technological success to the new boring machine, invented by the foundry master Jean Maritz, which both bored and turned a solid-cast cannon in more regular manner.[72] But this account invokes technology as an external resource which drives social change. In fact, the precision of Gribeauval's new cannon was relative, not just to what came before, but of each cannon's bore to its respective cannonball, and of every cannonball to every other. Certainly, a narrow windage increased the accuracy and force of fire. But this advantage would be lost if a cannonball picked at random (from within that calibre) could not be easily loaded into the bore of any cannon (of the appropriate calibre). Hence, the story of how the Gribeauvalists tightened the fit of the cannon's bore to the cannonball – thereby making both bores and balls (respectively) functionally interchangeable – must include an account of how standards of production were enforced.

Let us begin with the bore itself. Whereas the previous generation of engineers had relied on the experienced 'eye' of the examining officer to inspect its inner diameter, the Gribeauvalists substituted a portable gauge, called the *étoile mobile*, which measured the inner diameter to within 0.025 millimetres (see Figure 2). Fashioned by a scientific instrument-maker and carefully calibrated by the same hand at the Strasbourg arsenal, one *étoile mobile* was distributed to each of the kingdom's foundries to ensure a uniform standard.[73] But this did not mean that all conflicts came to an end. A cannon, like most artifacts of commerce and war, cannot be defined with the requisite degree of completion. Even the verification of the shape of cylindrical cannon bores could not be transformed into a mechanical operation. And so long as the inspection depended on the skill and discretion of the inspector, there was room for controversy. As the foundry master at the Strasbourg armoury noted, an inspector examining one of his cannon bores could easily – 'even involuntarily' – tilt the *étoile mobile* ever so slightly. 'Two examiners', he pointed out, 'almost always obtain different results'.[74] As someone whose livelihood depended on satisfying these state specifications, he was understandably concerned about this.

To minimize such disputes, regulations in the last decade of the *ancien régime* prescribed ritualized inspection procedures and well-defined tolerances of production. First came a test with the *étoile mobile*, then a test with a mirror, then a test with a hook to check for crevices, then a test with a wax imprint to check the depth of the crevices, and then all of these steps were repeated after the cannon had been test-fired twice. Throughout these proceedings, a written log was kept and every page signed by both the supervising inspector-officer and the foundry master. And at any point, if any inspection revealed that any of several dimensions of the cannon deviated from a set of prescribed tolerances, the cannon was rejected.[75]

To minimize such disputes still further – and substantiate the idealized pictures in their *Tables de construction* – the Gribeauvalists developed additional instruments and circumscribed the *practice* of gauging. Consider here the other crucial parameter affecting the windage of the cannon: the dimensions of the cannonball. European artillerists had long passed their cannonballs through a circular 'go' gauge (a *lunette*) to make sure in advance that the shell would fit into the barrel. This, however, left the lower threshold for the size of the ball undefined, and hence dependent on the on-the-spot judgement – the 'eye' – of the cannoneer. The Gribeauvalists now supplemented this 'go' gauge with a 'no-go' gauge whose diameter measured 9 *points* less (see Figure 4).[76] This defined a zone of tolerance quite clearly in concrete terms, and also immediately made it a matter for intense negotiation. The service had initially tried to set the tolerance at 6 *points*, but the private manufacturers of cannonballs had protested that such a narrow band of tolerance would be too expensive to achieve, and they convinced the service to settle for a 9-*point* band.[77]

Yet even defining the band in this way was not sufficient. As the Gribeauvalists soon realized, this tolerance for the circumference of the cannonball failed to capture the variation in the ball's *shape* that they needed to control. For instance, an oblong cannon ball might successfully pass through the 'go' *lunette* and still not fit into the barrel of the gun. (Imagine the shape of an American football.) Hence, the Gribeauvalists replaced these flat *lunettes* with a cylindrical tube through which the ball was passed. But what if the inspector simply let an oblong ball drop down the tube? To minimize this problem, the Gribeauvalists affixed these cylinders at an oblique angle to special workbenches. Now a ball would have to roll down the tube.[78]

Finally, the Gribeauvalists recognized that these gauges might vary among themselves and over time with repeated use. Their solution was to have all gauges made in Strasbourg by 'a single hand' and verify them periodically against a master standard, which was *itself* defined by a tolerance band, such that gauges were discarded if they varied by more than 2 *points* from the norm.[79] Ultimately, this hierarchy of standards extended all the way to the royal system of measures. Gribeauval converted all the French arsenals from local measures to the *pied du roi*, which the

Academy of Sciences had calibrated with reference to measurements taken from 'nature'. This was part of a broader impetus toward standardization of measurements in the administration of the 18th-century state. In this way, a hierarchy of measures mirrored a hierarchy of material objects and its carefully ranked administrators.[80]

This minutely choreographed gauging of cannonballs shows the effort the Gribeauvalist engineers had to exert to forestall all possible subversions of their rules. The apparent objectivity of their interchangeable cannonballs was the outcome of this process. Yet to discipline artifacts effectively, this elaborate structure, created by the engineers, had to constrain them as well. At bottom, the engineers themselves had to accept precision as something more than an operational necessity. As the recent volume edited by Norton Wise makes clear, if experts seek precision, it is because they come to believe in it as a moral imperative. Precision is a *value*.[81] Gribeauval was forever reminding his subordinates that his demands for precision were not 'hairsplitting'. 'It is perhaps by lack of attention . . .', he scolded, 'that the [cannon] balls of M. Maritz are too small'.[82]

Despite a panoply of institutional safeguards, then, human resolve remained essential to this programme of socio-technical discipline. Artillery professor Jean-Louis Lombard noted that engineers would be judged

FIGURE 4
Go, No-Go Gauges for Cannonball

This pair of gauges defined the minimum and maximum diameters for cannonballs of a particular calibre. The difference between their diameter – and hence their tolerance – is 10 *lignes* (or about 1.8 mm). They date from the revolutionary period. The inserts preserved the gauges from damage.

Source: from the Musée de l'Armée (Paris), K22533.

by their ability to produce 'precision, solidity, and uniformity'. Any failure to do so would be a blight on their honour because it implied a lack of diligence in their duty to the state.

> And in all regards their conduct must be that of a scrupulous character. For if there is an error, with whom should the responsibility lie? – With those in whom the government placed its trust and who by either criminal abuse, ignorance, or negligence have delivered to the service materials whose defects may have disastrous consequences.[83]

The price of standards is eternal vigilance.

Klingenthal: An Armoury in Crisis

So far, I have presented this hierarchy of standards, representations and mechanical authorities as a logical structure which made artifacts objective. In the remainder of this paper, I will give a brief, 'thick' account of how this sort of hierarchical structure could emerge historically as a response to conflict and negotiation. Doing so will highlight the way the resolution of conflict in the workplace depended on the sorts of pressures – including political clout and physical force – which the various parties could bring to these negotiations. It will thereby show how the resolution of conflict through the creation of more objective objects also meant defining the political and social status of the various players involved in the productive process.

My story comes from the hamlet of Klingenthal, located thirty kilometres from Strasbourg. There, in the 1730s, the French state created *ex nihilo* an armoury to serve as the army's premier source of swords, sabres and bayonets. A designated merchant (known as the 'Entrepreneur') operated the armoury there on the basis of a royal patent that accorded him various privileges, including tax exemptions and a quasi-monopoly. The armoury itself was staffed by highly skilled Protestant German artisans who had been brought in from the steel-working town of Solingen. In return for their commitment to move to France to work on military weaponry, these artisans were also accorded various privileges, including dispensation from certain taxes, exemption from army service and free housing. They were also nominally subject to military discipline. These artisans were relatively prosperous, compensating for fluctuations in military demand by filling private orders for fancy swords. The Lutherans among them were allowed to have their own parish and pastor (because that was a provincial privilege of Alsace, itself a particularistic legal entity within the absolutist kingdom of France). And the Calvinists among them (who enjoyed no such exemption) were allowed to have a school teacher who secretly doubled as their pastor. In short, the manufacture operated on the corporatist assumptions which governed the *ancien régime*'s legal, social and material life. This was a moral economy, as well as a productive one.

In 1765, however, an engineer-inspector from the artillery service was housed in the town for the first time. This was the time of the Gribeauvalist reform of the artillery. And when those reforms were finally consolidated in 1777, the artillerists turned their attention to small arms. A new musket was introduced, which the Gribeauvalists hoped to manufacture with unmatched precision. And in short order, a new inspector-engineer, Ami-able-Marie Givry, was sent to Klingenthal to take a firmer hand over production, and to enforce rigorous standards. In return, the Entrepreneur, Louis Gau, a well-connected merchant from Strasbourg, began to agitate for an increase in the price of bayonets.[84]

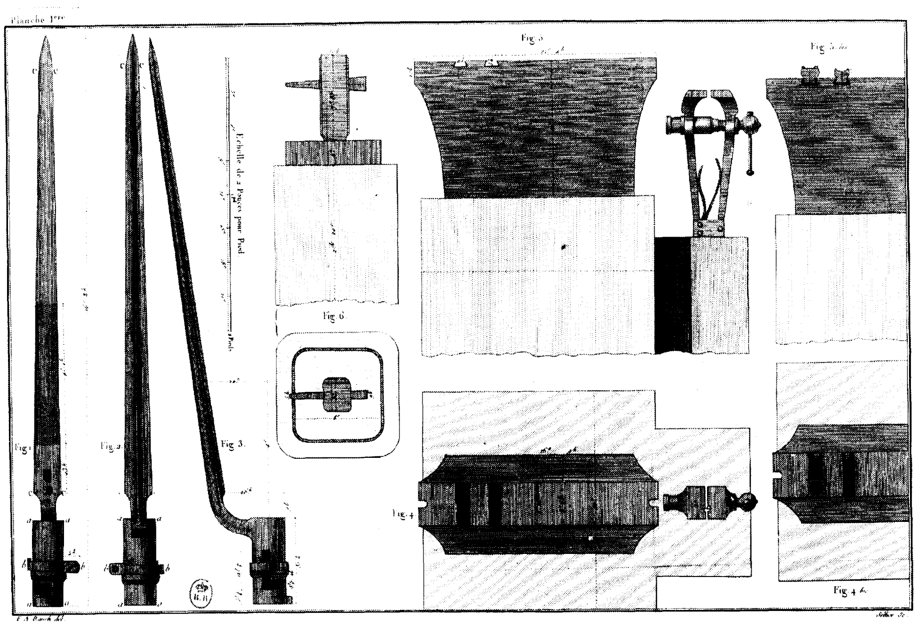
In the early 1780s, Klingenthal was the site of disturbances. The dispute focused in particular on the dimensions of a metal ring, called the *douille*, which affixed the bayonet to the muzzle of the musket (see Figure 5, overleaf). The bulging circle at the end of the ring was still positioned by eye. Positioned incorrectly, it impeded the correct attachment of the bayonet to the musket. If the bayonet ring could be precisely defined, it would save the state the expense of transporting bayonets halfway across France from Klingenthal to Saint-Etienne to be individually hand-fitted to gun barrels and then returned to the border (near Klingenthal). At issue was the French state's ability to coordinate activities across the kingdom by matching the gun barrels of its Catholic artisans in Saint-Etienne to the bayonet rings of its Protestant artisans in Klingenthal.[85]

But when, in 1783, Inspector Givry ordered the ring-forgers to conform to the new model, they refused, claiming that the artillery was altering the terms of its own contract. After all, they noted, none of the 8000 rings they had made and sold to the artillery since the publication of the regulations of 1777 would have been acceptable under the new standard. Where was the law authorizing the new model? And the ring-*filers* complained as well. They noted that the new standard had increased the number of rings rejected by inspectors as defective, and that this had halved the number they could file in a day, and hence had halved their wages too. The merchant Gau began to bring pressure to bear at Court.[86]

When Inspector Givry was recalled to Paris to explain his position, the confrontation took a violent turn. In his absence, Givry's second-in-command, Captain Villeneuve, ordered one of Klingenthal's controllers, François-Antoine Bisch, to construct a new stamping die and companion jig, and to distribute one to every ring-forger (see Figure 6, overleaf). These controllers were the state employees who actually wielded these inspection instruments, and as such, were the first to face the hostility of artisans whose pieces they rejected. According to Villeneuve, the demand for this 'degree of perfection' precipitated a violent mutiny among the forgers.[87] In the face of the forgers' refusal, Captain Villeneuve issued an order – translated into German – that all workers gather on the morning of 2 April to receive the new gauges. Disobedient workers, he added, would be imprisoned. At that morning meeting, a group of forgers, led by Jean Schmidt, scoffed at the young officer, telling him (in Villeneuve's words):

> . . . that they had no need to take instruction from me; that they all knew their trade; that they would continue to make the rings just as they had up till now; and that if we didn't want them, we should [get them elsewhere];

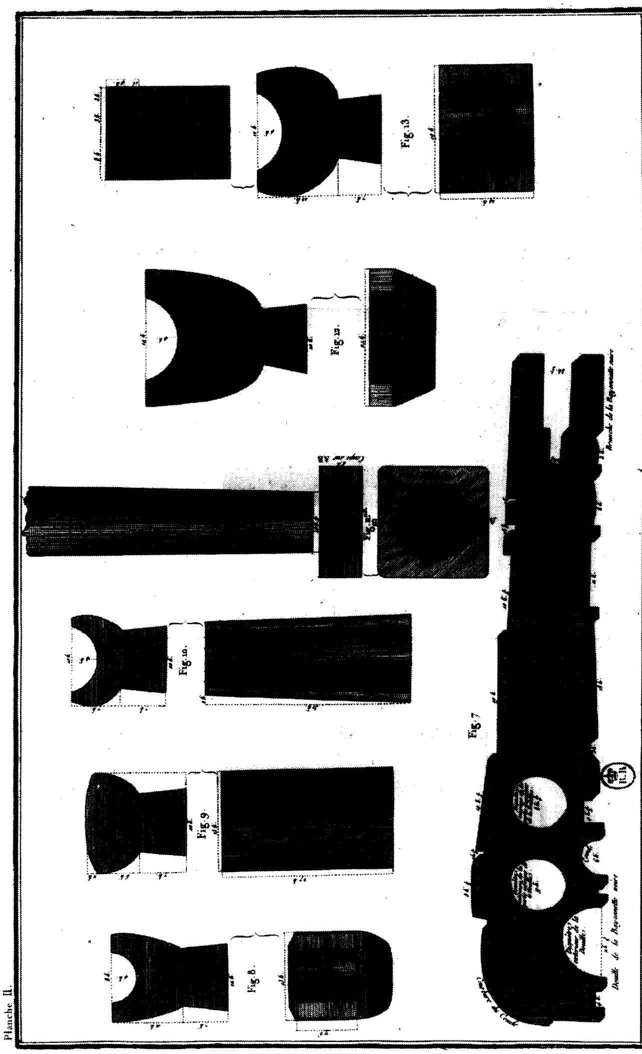
FIGURE 5
Projective Views of Bayonet and Forging Tools



These projective views of the bayonet (on the left) and tools for forging bayonets come from Plate 1 of Vandermonde's *Procédés de la fabrication des armes blanches* (1793–94). The bayonet's ring (*douille*). is the lower portion of the bayonet which is then attached to the bayonet's muzzle. The bulging circles which positioned the ring can be seen at the bottom of the image.

Source: from the Bibliothèque Nationale (Paris).

FIGURE 6
Gauge and Production Tools



This drawing of a gauge and other production tools comes from Plate 2 of Vandermonde's *Procédés de la fabrication des armes blanches* (1793–94). The two holes in the gauge (lower left) are to verify the upper and lower interior diameters of the ring, and the half-circle cutout is to verify its outer diameter.

Source: from the Bibliothèque Nationale (Paris).

> and that it was no business of mine to interfere with whether the rings were well or poorly made for the filers.[88]

Brought back to work by fear of imprisonment, the forgers demanded to see the new regulation which proposed this standard, and if it were true, demanded a price raise to compensate them for the additional work effort. If not, they threatened to quit the manufacture and go back to Germany.[89]

Villeneuve's refusal to consider such a request, translated into German, caused the artisans to storm out a final time. They threatened harm to Bisch and to his wife, met in a cabaret to swear their defiance, and filed a petition of complaint with the Marquis de Lasalle, the provincial army commander. Two days later, Villeneuve, with the assistance of the rural police force, the *maréchaussée*, sent the mutinous Schmidt and his associate Hiet to prison. When their comrades demanded to be arrested as well, Villeneuve ordered the police to bind in irons the arms and legs of anyone who presented themselves at the jail.[90]

This episode came quickly to the attention of a high commission then entrusted with reforming the military. The commission took note of the complaints of the workers, as relayed by Lasalle, and they learned from Entrepreneur Gau that Inspector Givry kept the master patterns locked up in his office. Gau further accused Givry of seeking to nationalize the manufacture. This was not implausible; a proposal to this effect was under discussion at the time. Already the state had usurped the merchant's role in setting prices for individual parts of the musket and its bayonet. Might it not now simply place the entire operation under its direct ownership? For his part, Givry denied that he had altered the standards. In a somewhat contradictory vein, however, he conceded that certain artisans perhaps ought to be paid more since 'their [former] prices had been calculated on the basis of a tolerance [that had proved to be] inimical to the king's interests'. In fact, the old 1777 regulations had said *nothing* about tolerances for the ring. Givry announced that he would henceforth accept ring diameters forged within 1 *point* of the final filed size. But workers must not be allowed to judge his 'greater or lesser exactitude'. Armourers who questioned the authority of military officers should be imprisoned. Indeed, all armourers who were under contract to the army – in return for their tax exemptions – were subject to military discipline.[91]

What was to be the state's role in production? What powers did it have over producers? In this case, we are dealing with a three-cornered conflict where no party had a clear upper hand. The artisans could shift their efforts to other forms of work or return to Solingen; the merchant could undermine the quality of production or simply quit this form of commerce; and the engineers could cut (or raise) prices and standards. Moreover, all parties could call on powerful patrons, appeal to certain legal privileges, and muster some kind of physical force. At stake, too, was the status of French subjects: did the state have the right to imprison artisans who refused to work on terms which they considered unacceptable? Also at issue was the boundary between state interests and private capital: could the government oblige a merchant to trade in an unprofitable manner or would it proceed from managing workshops to the direct ownership of the means of production? The answer to these questions cannot be understood in narrow technological terms, but only within the political framework of late *ancien régime* France. In defining a tolerance for this artifact, the state defined its relationship to its citizen-producers.

In its ruling, the military commission attempted to adjudicate the boundary between administrative and economic rationality, and between the interests of the state and the interests of local merchants and artisans. At the root of the problem, the Commission acknowledged, was the 'natural animosity' between merchant and inspector: the one sought profits, the other sought to serve the state. The Commission's solution, therefore, was to demarcate their respective spheres of authority. The inspector's powers did *not* extend to the 'interior' of the manufacture, they now acknowledged. Power over the hiring of workers, their pay, or the use of their time 'belonged to the [merchant]'. The inspector, however, set the standards for raw materials and finished goods, and for 'general work'. The Commission then proceeded to define this political border in physical terms. It pointed out that the artillery service could *not* expect the manufacture to turn out perfect bayonets, only ones of 'good quality up to a certain degree'. If the state wanted more precisely tooled weapons, it would have to 'fix the degree of rigour with which the inspection was to be carried out, according to the amount the king is willing to pay'. The Commission then asked the artillery to draw up a *procès-verbal* – a detailed public document – indicating exhaustively the tolerances to which bayonets would have to conform and the procedures by which the degree of conformity would be judged. These standards and procedures necessarily had to be public, and the Comité ordered the artillery service to give the merchant a copy of the new master patterns. It also ordered the military engineers to desist from incarcerating artisans without first obtaining permission from the civil courts.[92]

Givry accounted this a victory for the artillery service – though he warned Villeneuve that in the future they would have to document their every decision. A year later Givry did in fact spell out a variety of tolerances for the bayonet. New master patterns and gauges were distributed to the central War Office, to the inspector and to the Entrepreneur. When these standards were conveyed to the armourers, however, they balked again. Givry then offered them prices that accorded with what he estimated was a 10 *livres*/week profit, and which he reckoned was 'not bad for men housed by the state' – but they again refused. Only when Givry received authorization from the minister of war to strike recalcitrant workers permanently from the rolls and deprive them of state work, did the artisans give in. Klingenthal produced highly precise bayonets until the upheaval of the Revolution.[93]

On one level, then, the engineers had triumphed. But they had succeeded only by renegotiating the terms of the exchange. Confronted with recalcitrant producers and under pressure from civilian authorities, the military engineers were forced to make the terms of that exchange explicit and public. Givry had vowed that he would not allow artisans to question his judgement. In fact, his discretion had been reduced. Objective criteria, enshrined in material tools and codified in routines, henceforth defined the bayonet ring. A few years later, in the early years of the Revolution, Monge's scientific colleague, Alexandre Vandermonde, was sent to Klingenthal to report on the methods of production used there – and spread this information to other French metalworkers and armourers. He supervised the publication of new and exact mechanical drawings – produced with strict orthogonal projection – which for the first time defined the bayonet, its constituent parts, and all its gauges (see Figures 5 and 6).[94] The public objectivity of the bayonet was an outcome of social conflict.

From the artisans' point of view, their mutiny had enabled them to extract greater payments from the state. In doing so, they had obliged the state engineers to acknowledge their rights as citizen-producers, free to place their labour and capital where they wished. Yet even this victory was necessarily contingent. During the decades of the Revolutionary and Napoleonic wars, the political clout of the artisanal class and the economic leverage of arms-workers waxed and waned with the fortunes of various governments, and with the ebb and flow of military campaigns. In general, the conditions of war enabled the armourers to oblige the state engineers to relax tolerances, even to undo objective standards altogether and revert to simple tests of functionality. There were also periodic attempts – generally resisted – to assimilate arms-workers back under military discipline.[95] The relationship between manufacturing tolerance and political toleration was a historically specific one.

Citizenship, Capitalism and the Making of the Modern French State

It is outside pressure and political struggle, however, that obliges those in power to articulate *public* standards. In doing so, they are made to spell out the limits of their personal power, even as they bid fair to establish a different kind of mechanical authority. The conflict at Klingenthal obliged the absolutist state to specify its standards of production, while allowing producers (both artisans and merchants) the latitude to decide how to meet those standards – or get out of the business if they saw fit. In other words, the contending parties agreed to an exchange: in return for the king's coin, producers agreed to supply a well-defined commodity. But the process by which the terms of that exchange were made public and verifiable involved a political struggle which depended on the relative power of military engineers, merchant capitalists and (Protestant) artisans. The fact that this process of public negotiation could take place at all suggests a new recognition by the state of the autonomy of its citizens. Not least of the outcomes was the recognition that these Protestants deserved to be tolerated and protected by civil law – if only for the good of the state. A few years later, in 1787, Louis XVI extended full civil rights to Protestants for the first time since the revocation of the Edict of Nantes.

In effect, the absolutist state had agreed to allow the producers to constitute themselves as private citizens and as economic agents. This equation was part of a larger claim, articulated by the Abbé Sieyes and others in the run-up to the French Revolution, that the members of the third estate, because of their capacities as producers, were alone entitled to claim the title of 'citizen' (and, not incidentally, to deny that title to parasites like aristocrats and women).[96] This equation was part of a larger struggle in the 18th century during which tolerance – both political toleration and manufacturing tolerance – came to demarcate the boundaries between spheres not previously seen as distinct. The rise of political toleration can be understood as an attempt to mark an increasingly well-defined boundary between the authority of the sovereign and what we now call the private actions of his subjects. This juridical boundary was given fuller articulation in the declaration of the Rights of Man, and partially codified in the civil laws of the Revolutionary period.[97]

During that same period, the state's rules regarding the invention, production, and consumption of artifacts came to be defined in formal terms, rather than in terms of particularistic privileges granted on an individual basis. And, more generally, economic relationships between the state and its citizen-producers were henceforth defined in public terms, rather than as a matter of private law or the moral obligation of subjects. This explains, for instance, the thinking behind the infamous d'Allarde and Le Chapelier laws of 1791, which forbade all forms of association among workers and merchants. This development was of a piece with the emergence of manufacturing tolerance as a way to define the boundary between the state's need for the commodities and the right of its subjects to make an economic livelihood. The juridically limited state and the decentralized capitalist order which came to the fore at the end of the 18th century brought to an end the particularistic legal status which both persons and artifacts had enjoyed under absolutism. One might even say that henceforth objects could, in some sense, be considered 'objective'.

That is *not* to say that the French state ceased to be heavily involved in many aspects of trade and production. Military production, in particular, remained closely supervised by the state. But even the armaments industries remained in private hands, and the relationship between the state and these gun producers took an increasingly contractual form. Indeed, the state, more generally, continued to play a crucial role as the guarantor of this new public economy: balancing the rights of inventors with their obligation to publish their discoveries (via the patent system); ensuring the open dissemination of knowledge (via the Conservatoire of Arts et Métiers and its collections of machines and technical drawings); enforcing uniform national weights and measures (via the metric system and the Bureaux des Poids et Mésures); and regulating standards of quality production (in many industries).[98] This crucial role of the state as guarantor of public standards was given theoretical voice in this period by the holder of the world's first academic post in economics, the same Alexandre Vandermonde who was curator of the Conservatoire des Arts et Métier, champion of interchangeable parts manufacturing, advocate of the metric system, and supervisor of the collection of technical drawings of the bayonets, gauges and machines of the Klingenthal armoury. Not only did Vandermonde emphasize the value of manufacturing to the French economy, he also advocated a middle road of regulated markets that mirrored much of French economic policy in this period.[99]

Neither should this new 'objectivity' of modern artifacts be understood to imply that these artifacts ceased to have different meanings for different people, nor that they have ceased to bear political values. Rather, one might say that these artifacts now participated in an asymmetrical form of objectivity, which appeared less stringent to those further up the social and productive hierarchy. To the armourer, a bayonet continued to embody a thousand skilful strokes of the file, a batch of iron with an unusual sheen, a quarrel with his journeyman, and the means to get a livelihood – so long as he met the public standards of production. To the engineer-inspector, a bayonet represented an imperfect replica of a thousand other bayonets which must be supplied to the king's armies, for honour's sake – and for the sake of promotion. And as for the soldier who wielded that bayonet in battle, for him the blade was a help-mate which might impale a mustachioed Prussian. Different individuals will always generate diverse meanings about the artifacts of daily life. Yet the fact that the soldier could choose any bayonet and still fit it on to the muzzle of his gun – even though the two pieces of metal had been manufactured several hundred kilometres apart – testifies to the fact that technical knowledge had been taken out of the domain of private and local knowledge, and moved up to a more general level of organization. Hence, the values embedded in these objects were typical of those large systems which operate according to the ethos of efficiency, coherence and centralized control. It is no accident that these mass interchangeable bayonets proved eminently suitable for the mass army fielded by the French régime during the Revolutionary wars.

Finally, even though the instruments of mechanical drawing and manufacturing tolerance made the French engineers the masters of the technological hierarchy of the post-Revolutionary French state, it did *not* thereby place them in command of the French economy or of the merchant capitalists who increasingly controlled production. This is not the place to retell the familiar story of the École Polytechnique and the hierarchy of engineering and technical schools that emerged under the sponsorship of the post-Revolutionary state.[100] Crucial to this structure, however, was a concomitant hierarchy of cognitive knowledge, with technical drawing as one of its main pillars. Yet the power of the engineers was always limited in important respects, and the actual realization of their drawings and plans was always left in the hands of private firms who managed their own affairs according to the criteria of profit and return on investment. Indeed, this particular mix of state supervision and private capital has remained characteristic of French statism until the recent past. And not until the latter part of the 19th century would the managers of private industrial firms be ready to take advantage of the lesson the state engineers had discovered in the 18th century: the power of these instruments to coordinate far-flung operations *and* the need continually to elaborate these instruments in response to the conflicts they invariably engendered.

Conclusion: Making Things the Same

Today, artifacts travel with increasing ease over much of the globe. Transformers adapt personal computers to local currents; bicycle parts are sized in metric dimensions (even in the USA!); quantitative standards for copper, wheat and air pollution are monitored by international agencies; and digital high-definition television is coming. In factories from Thailand to Tennessee to the Czech Republic, digitally controlled machine tools can be programmed (and reprogrammed) to produce functionally identical artifacts in short production runs. For all the diversity of our consumer cornucopia, the banal artifacts of the world economy can be said to be more and more impersonal, in the sense that they are increasingly defined with reference to publicly agreed-upon standards and explicit knowledge which resides at the highest level of organizations, rather than upon local and tacit knowledge that is the personal property of skilled individuals. This is true even though the heyday of Fordist mass production is said to be over. Flexible production depends on standards of production as much as, perhaps even more than, Fordism: in part because shared values and common standards enable congeries of independent producers to pool their efforts and simultaneously compete against one another.

Again, this is not to say that different peoples and cultures have ceased to invest the 'same' artifact with different meanings, nor that artifacts and agreed-upon standards have ceased to carry political values. On the contrary, this paper suggests that the seeming objectivity of these artifacts and standards can best be understood as the outcome of social conflict and negotiation. Scholars of contemporary technology have persuasively argued that cutting-edge technologies – ballistic missile guidance systems, say – remain the product of local and tacit skills. And scholars of the contemporary workplace have shown that even in factories with computer-aided production, shop-floor workers retain considerable discretionary power over the means of production. Things remain thick – thick with material obstinacy, and thick with diverse meanings.[101]

Nevertheless, the mundane and multiple technologies of our commercialized and militarized economy have become more capable of travel, if only because they can everywhere be plugged into vast technological systems, themselves regulated and kept running smoothly by standardized 'instruments' such as mechanical drawing and machine tools (themselves increasingly computerized). An explanation of how and why this process has developed over the past century would take us far beyond the confines of this paper. What I have attempted here, rather, is to describe some of the modest early 18th-century efforts to 'make things the same'.

Notes

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In my annotations below, I will use the abbreviation 'SHAT' when I am drawing on documents in the archives of the Service Historique de l'Armée de Terre (Vincennes, France), and 'AN' for documents in the French Archives Nationales (Paris).

1. Merritt Roe Smith, *Harpers Ferry Armory and the New Technology: The Challenge of Change* (Ithaca, NY: Cornell University Press, 1979); David Hounshell, *From the American System to Mass Production, 1800–1932: The Development of Manufacturing Technology in the United States* (Baltimore, MD: Johns Hopkins University Press, 1983); Ken Alder, *Engineering the Revolution: Arms and Enlightenment in France, 1763–1815* (Princeton, NJ: Princeton University Press, 1997).
2. Daniel Headrick, 'Information Systems and the History of Technology in the Eighteenth and Early Nineteenth Centuries', paper given at 1997 SHOT conference (Pasadena, CA, October); Shoshana Zuboff, *In the Age of the Smart Machine: The Future of Work and Power* (New York: Basic Books, 1988). See also Kathryn Henderson, 'Flexible Sketches and Inflexible Data Bases: Visual Communication, Conscription Devices, and Boundary Objects in Design Engineering', *Science, Technology, & Human Values*, Vol. 16, No. 4 (Autumn 1991), 448–73.
3. The classic collection outlining the social constructivist agenda is Wiebe E. Bijker, Thomas P. Hughes and Trevor Pinch (eds), *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (Cambridge, MA: MIT Press, 1987); see also the follow-up volume, edited by Bijker and John Law, *Shaping Technology/Building Society: Studies in Sociotechnical Change* (Cambridge, MA: MIT Press, 1992). For perhaps the two best realizations of this programme, see Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge, MA: MIT Press, 1990), and Wiebe E. Bijker, *Bicycles, Bulbs and Bakelite: Toward a Theory of Sociotechnical Change* (Cambridge, MA: MIT Press, 1995).
4. Arjun Appadurai (ed.), *The Social Life of Things: Commodities in Cultural Perspective* (Cambridge: Cambridge University Press, 1986).
5. Langdon Winner, 'Upon Opening the Black Box and Finding It Empty: Social Constructivism and the Philosophy of Technology', *Science, Technology, & Human Values*, Vol. 18, No. 3 (Summer 1993), 362–78. See, however, Gabrielle Hecht, *The Radiance of France: Nuclear Power and National Identity after World War II* (Cambridge, MA: MIT Press, 1998, forthcoming); Hecht, 'Rebels and Pioneers: Technocratic Ideologies and Social Identities in the French Nuclear Workplace', *Social Studies of Science*, Vol. 26, No. 3 (August 1996), 483–530.
6. For two different approaches to taking this potency into account, see: Daniel Headrick, *The Tools of Empire: Technology and European Imperialism in the Nineteenth Century* (New York: Oxford University Press, 1981); and Michael Adas, *Machines as the Measure of Men: Science, Technology, and Ideologies of Western Dominance* (Ithaca, NY: Cornell University Press, 1989). Norton Wise has recently focused on the importance of 'travelling' to account for the claim of technical and scientific universalism: see M.

Norton Wise (ed.), *Values of Precision* (Princeton, NJ: Princeton University Press, 1995), esp. 92–100.

7. The relationship between the two revolutions in France has been systematically ignored for the past 20 years, principally because of the anti-Marxist 'revisionist' school on the French Revolution, which has shied away from materialist-social causes of the French Revolution and has focused exclusively on its political cultural preconditions: see George Taylor, 'Non-Capitalist Wealth and the Origins of the French Revolution', *American Historical Review*, Vol. 72 (1967), 469–96; François Furet, *Penser la Révolution française* (Paris: Gallimard, 1978). There is, however, a revival of interest in material culture as a site for the examination of tensions within the *ancien régime*: see Colin Jones, 'Bourgeois Revolution Revivified: 1789 and Social Change', in Colin Lucas (ed.), *Rewriting the French Revolution* (Oxford: Clarendon Press, 1991), 69–118.
8. On *ancien régime* particularism, and challenges to it from the legal profession, see David A. Bell, *Lawyers and Citizens: The Making of a Political Elite in Old Regime France* (New York: Oxford University Press, 1994). On *ancien régime* particularism, and the challenge to it from the new ideal of civil society, see Daniel Gordon, *Citizens without Sovereignty: Equality and Sociability in French Thought, 1670–1789* (Princeton, NJ: Princeton University Press, 1994). The best account of the modernizing monarchy remains Alexis de Tocqueville, trans. Stuart Gilbert, *The Old Régime and the French Revolution* (Garden City, NY: Doubleday, 1955).
9. John Locke, *A Letter Concerning Toleration* (London: Churchill, 1689); Pierre Bayle, *De la tolération: Commentaire philosophique sur ces paroles de Jésus Christ* (Paris: Presses pocket, 1992); Voltaire, *Dictionnaire philosophique*, ed. Raymond Naves and Julien Brenda (Paris: Barnior, 1967), 401–07; Immanuel Kant, *An Answer to the Question, What is Enlightenment?*, in *On History*, trans. Lewis White Beck, Robert E. Anchor and Emil L. Fackenheim (Indianapolis, IN: Bobbs-Merrill, 1963). For a general analysis, see Susan Menus, *Toleration and the Limits of Liberalism* (Atlantic Highlands, NJ: Humanities Press International, 1989). For a historical study, see Geoffrey Adams, *The Huguenots and French Opinion, 1685–1787: The Enlightenment Debate on Toleration* (Waterloo, Ontario: Canadian Corporation for Studies in Religion, 1991). For Voltaire in action, see David Bien, *The Calas Affair: Persecution, Toleration, and Heresy in Eighteenth-Century Toulouse* (Princeton, NJ: Princeton University Press, 1960).
10. Theodore Porter, *Trust in Numbers: Objectivity in Science and Public Life* (Princeton, NJ: Princeton University Press, 1995). See also Lorraine J. Daston, 'Objectivity and the Escape from Perspective', *Social Studies of Science*, Vol. 22, No. 4 (November 1992), 597–618; Daston, 'The Moral Economy of Science', *Osiris*, Second Series, Vol. 10 (1995), 3–24.
11. François Blondel, *L'art de jetter les bombes* (Leyden: n.p., 1685), Preface.
12. Geertz himself borrowed the term from Gilbert Ryle: see Clifford Geertz, *The Interpretation of Cultures* (New York: Basic Books, 1973), 3–30.
13. Gaston Bachelard, *Le nouvel esprit scientifique* (Paris: Presses Universitaires de France, 3rd edn, 1980), esp. 55, 65–67, 136–40. As Peter Galison points out, Bachelard's view that instruments are reified theories underestimates the autonomous history of such instruments and their makers. Indeed, Galison's work suggests that modern physics, too, relies in part on a material culture which is amenable to a 'thick' analysis of how diverse and contending actors are able to reach partial agreement and make exchanges: see Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago, IL: The University of Chicago Press, 1997), 18.
14. Thomas P. Hughes, 'The Evolution of Large Technological Systems', and John Law, 'Technology and Heterogeneous Engineering: The Case of Portuguese Expansion', in Bijker, Hughes & Pinch (eds), op. cit. note 3, 51–82, 111–34.
15. Bruno Latour, 'Drawing Things Together', in Michael Lynch and Steve Woolgar (eds), *Representations in Scientific Practice* (Cambridge, MA: MIT Press, 1990), 20–69, esp. 26–35.

16. David Landes, *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present* (Cambridge: Cambridge University Press, 1969); Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress* (New York: Oxford University Press, 1990).
17. Alfred Chandler, *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, MA: Harvard University Press, 1977).
18. For one influential statement regarding proto-industrialization, see Peter Kriedte, Hans Medick and Jürgen Schlumbohn, *Industrialization before Industrialization: Rural Industry in the Genesis of Capitalism* (Cambridge: Cambridge University Press, 1981).
19. Considerable empirical evidence suggests that a well-defined entrepreneurial role was slow to develop in much of continental Europe: see William Reddy, *The Rise of Market Culture: The Textile Trade and French Society, 1750–1900* (Cambridge: Cambridge University Press, 1984). Recently, Liu and Berg have noted that proto-industrialization theory takes for granted that industrializing capitalists will triumph over artisanal producers: Tessie P. Liu, *The Weaver's Knot: The Contradictions of Class Struggle and Family Solidarity in Western France, 1750–1914* (Ithaca, NY: Cornell University Press, 1994), 22–44; Maxine Berg, *The Age of Manufactures: Industry, Innovation, and Work in Britain, 1700–1820* (Totowa, NJ: Barnes & Noble Books, 1985), 77–86.
20. Charles Sabel and Jonathan Zeitlin, 'Historical Alternatives to Mass Production: Politics, Markets and Technology in Nineteenth-Century Industrialization', *Past and Present*, Vol. 108 (1986), 133–76. See their revised version of this argument in Sabel and Zeitlin (eds), *Worlds of Possibility: Flexibility and Mass Production in Western Industrialization* (New York: Cambridge University Press, 1997), 1–33.
21. William H. Sewell, Jr, *Work and Revolution: The Language of Labour in France from the Old Regime to 1848* (Cambridge: Cambridge University Press, 1981).
22. Michael Sonenscher, *The Hatters of Eighteenth-Century France* (Berkeley, CA: University of California Press, 1987); Sonenscher, *Work and Wages: Natural Law, Politics and the Eighteenth-Century French Trades* (Cambridge: Cambridge University Press, 1989).
23. See also Liliane Hilaire-Pérez, 'Invention and the State in 18th-Century France', *Technology and Culture*, Vol. 32, No. 4 (October 1991), 911–31.
24. Sonenscher, *Hatters* (1987), op. cit. note 22; see also Leora Auslander, *Taste and Power: Furnishing France* (Berkeley, CA: University of California Press, 1996). On measures and their transformation in this period, see Ken Alder, 'A Revolution to Measure: The Political Economy of the Metric System in France', in Wise (ed.), op. cit. note 6, 37–71.
25. Simone Meyssonnier, *La balance et l'horloge: La genèse de la pensée libérale en France au XVIIIe siècle* (Montreuil: Editions de la Passion, 1989); Elizabeth Fox-Genovese, *The Origins of Physiocracy: Economic Revolution and Social Order in Eighteenth-Century France* (Ithaca, NY: Cornell University Press, 1976), 61–62, 100–03, 304–06. For the distinction between market principle and marketplace, see Steven L. Kaplan, *Provisioning Paris: Merchants and Millers in the Grain and Flour Trade during the Eighteenth Century* (Ithaca, NY: Cornell University Press, 1984), 25–33.
26. Diderot, 'Art', in *Encyclopédie, ou dictionnaire raisonné des sciences, des arts et des métiers*, Vol. 1 (Paris, 1751), 713–18, at 716. For his attacks on secrecy, see Diderot, 'Encyclopédie', *Encyclopédie*, Vol. 5 (1755), 635–48, at 647.
27. On the critique of private justice and demand for a public sphere, see Sarah Maza, *Private Lives and Public Affairs: The Cause Célèbres of Prerevolutionary France* (Berkeley, CA: University of California Press, 1993). Diderot's critique of private technological knowledge is one of the few ways in which the *philosophes* extended Francis Bacon's programme. For the present distinction between current open science and proprietary technology, see Partha Dasgupta and Paul A. David, 'Toward a New Economics of Science', *Research Policy*, Vol. 23 (1994), 487–521.
28. Ken Alder, 'French Engineers Become Professionals, Or, Meritocracy Makes Knowledge Objective', in William Clark, Jan Golinski and Simon Schaffer (eds), *The*

Sciences in Enlightened Europe (Chicago, IL: The University of Chicago Press, forthcoming [1998]).

29. On the relationship between state structure, military power, and forms of production, see Charles Tilly, *Coercion, Capital, and European States, AD 990–1992* (Cambridge, MA: Blackwell, rev. edn, 1992); William McNeill, *The Pursuit of Power: Technology, Armed Force, and Society since AD 1000* (Chicago, IL: The University of Chicago Press, 1982); and Thomas Ertman, *Birth of the Leviathan: Building States and Regimes in Medieval and Early Modern Europe* (Cambridge: Cambridge University Press, 1997).
30. Lorraine J. Daston and Peter Galison, 'The Image of Objectivity', *Representations*, Vol. 40 (1992), 81–128; see also their *Images of Objectivity* (forthcoming).
31. Michael Lynch, 'Discipline and the Material Form of Images: An Analysis of Scientific Visibility', *Social Studies of Science*, Vol. 15, No. 1 (February 1985), 37–65.
32. Latour turns briefly and insightfully to engineering drawings, without explaining the particular historical circumstances which led engineers to seek this form of representation: see Latour, op. cit. note 15, 52–54.
33. Diderot, 'Art', op. cit. note 26.
34. Cynthia Koepp, 'The Alphabetical Order: Work in Diderot's *Encyclopédie*', and William H. Sewell, Jr, 'Visions of Labor: Illustrations of the Mechanical Arts before, in, and after Diderot's *Encyclopédie*', in Steven Kaplan and Koepp (eds), *Work in France: Representations, Meaning, Organization, and Practice* (Ithaca, NY: Cornell University Press, 1986), 229–57 and 258–86; Antoine Picon, 'Gestes ouvriers, opération et processus technique: La vision de travail des encyclopédistes', *Recherches sur Diderot et sur l'Encyclopédie*, Vol. 13 (1992), 131–47.
35. John R. Pannabecker, 'Representing Mechanical Arts in Diderot's *Encyclopédie*', *Technology and Culture*, Vol. 39, No. 1 (January 1998), 33–73.
36. On the importance and variety of drawing education in France, see Yves Deforge, *Le graphisme technique: Son histoire et son enseignement* (Seyssel: Vallon, 1981); and Antoine Léon, *La Révolution française et l'education technique* (Paris: Société des Etudes Robespierristes, 1968).
37. Michael E. Gorman and W. Bernard Carlson, 'Interpreting Invention as a Cognitive Process: The Case of Alexander Graham Bell, Thomas Edison, and the Telephone', *Science, Technology, & Human Values*, Vol. 15, No. 2 (Spring 1990), 131–64.
38. Auslander, op. cit. note 24, 88, 111–17.
39. Jean-Jacques Rousseau, trans. Allan Bloom, *Emile, or on Education* (New York: Basic Books, 1979), 143–46, 195–203.
40. [Jean-Jacques Bachelier], *Détails sur l'origine et l'administration de l'École Royale Gratuite de Dessin* (Paris, 1768). Enrolment is calculated from AN F17 2499: Bachelier to Min. Interior (19 December 1792). On the artisanal drawing schools, see Arthur Birembaut, 'Les écoles gratuites de dessin', in Roger Hahn and René Taton (eds), *Écoles techniques et militaires au XVIIIe siècle* (Paris: Hermann, 1986), 441–76. On the paradoxical Enlightenment attitudes toward popular education, see Harvey Chisick, *The Limits of Reform in the Enlightenment: Attitudes toward the Education of the Lower Classes in Eighteenth-Century France* (Princeton, NJ: Princeton University Press, 1981).
41. Jean-Jacques Bachelier, *Discours sur l'utilité des écoles élémentaires en faveur des arts mécaniques* (10 September 1766), 7–8; Bachelier, *Collection des discours* (Paris: Imprimerie Royale, 1790), 39.
42. *Lettres patentes du roi portant établissement d'une École Gratuite de Dessin à Paris* (20 October 1767); J.-J. Bachelier, *Collection des discours* [1771], 19.
43. The classic essay on the new Renaissance grammar of visualization is W.M. Ivins, *On the Rationalization of Sight* (New York: Metropolitan Museum, 1938). On the translatability of Renaissance perspective, see Samuel Y. Edgerton, *The Renaissance Discovery of Linear Perspective* (New York: Harper & Row, 1976).
44. For an excellent technical discussion of the different forms of mechanical drawing, see Peter Geoffrey Booker, *A History of Engineering Drawing* (London: Northgate, 1979).

For a general history of technical drawing and its bearing on engineering, see Eugene Ferguson, *Engineering and the Mind's Eye* (Cambridge, MA: MIT Press, 1992), 87–96.

45. René Descartes, *La dioptrique, les météores et la géométrie*, in *Discours de la méthode* (Paris: Fayard [1637], 1987), 71–208. One of Monge's exercises was to show how the descriptive geometry can be used to transform projective views into perspective views. The reverse transformation, however, is not possible.
46. Daston, 'Objectivity' (1992), op. cit. note 10; Daston & Galison (1992), op. cit. note 30; Bosse quoted in Mark Schneider, *Gerard Desargues, The Architectural and Perspective Geometry: A Study in the Rationalization of Figure* (unpublished PhD dissertation, Virginia Polytechnic Institute, 1984), 142. The phrase 'view from nowhere' comes from Thomas Nagel, *The View from Nowhere* (Oxford: Oxford University Press, 1985).
47. Amédée-François Frézier, *Elémens de stéréotomie à l'usage de l'architecture pour la coupe des pierres*, Vol. 1 (Paris: Jombert, 1760), ix–x. On drawing in the schools of the fortification engineers, see Bruno Belhoste, Antoine Picon and Joël Sakarovitch, 'Les exercises dans les écoles d'ingénieurs sous l'ancien régime et la révolution', *Histoire de l'education*, Vol. 46 (1990), 53–109.
48. SHAT 2a59: Le Pelletier, 'Instructions qui seront données sur le dessein à l'École d'Artillerie de Metz' (1749); Joseph Du Teil, 'Salle de dessin' (1786); 'École d'Artillerie de Metz' (October 1767); Saint-Auban, 'Instruction' (25 October 1765).
49. Gaspard Monge, 'Stéréotomie', *Journal de l'École Polytechnique*, Vol. 1 (year III [1795]), 1–14, at 1; Monge, *Géométrie descriptive, Leçons de l'an III* (Paris, year VII [1799]), xvi. On the methods of masons, see Lon Shelby, 'The Geometrical Knowledge of the Medieval Master Masons', *Speculum*, Vol. 47 (1972), 395–421.
50. Gaspard Monge, 'Développements sur l'enseignement adopté pour l'École Centrale des Travaux Publics', 21 ventôse, year II [11 March 1794], in Janis Langins, *La République avait besoin des savants; Les débuts de l'École Polytechnique: L'École Centrale des Travaux Publics et les cours Révolutionnaires de l'an III* (Paris: Belin, 1987), 227–47, at 245.
51. Harold Belofsky notes that the descriptive geometry comes in two 'dialects', which are the product of distinct and contingent historical developments: H. Belofsky, 'Engineering Drawing – A Universal Language in Two Dialects', *Technology and Culture*, Vol. 32, No. 1 (January 1991), 23–46, at 32–34.
52. SHAT 2a59: Joseph Du Teil, 'Salle de dessin' (1786). For a text on shadows used by students at the military engineering school at Mézières in the late *ancien régime*, see [Monge?], 'Traité des ombres dans le dessin géométral' [1774], in Théodore Olivier (ed.), *Applications de la géométrie descriptive* (Paris: Carillian-Goeury, 1847), 6–8. For a text from the Revolutionary period, see Monge, 'Stéréotomie', op. cit. note 49, 9. Today, manuals still warn students of the difficulties of reading technical drawings: see, for example, W. Abbott, *Technical Drawing* (London: Blackie, 1962), 14. Auslander points out that while artisans produced shaded drawings for potential customers, they did not shade the private drawings they used in production: Auslander, op. cit. note 24, 334–37.
53. A.L. Lavoisier, *Réflexions sur l'instruction publique* (August 1793), in *Oeuvres de Lavoisier*, Vol. 6 (Paris: Imprimerie Nationale, 1862–93), 516–58, at 523.
54. See the argument and original documents collected in Langins, *République* (1987), op. cit. note 50; and Belhoste, Picon & Sakarovitch, op. cit. note 47.
55. See Léon, op. cit. note 36. On technical drawing as a tool for social advancement, see Patrice Bourdelais, 'Employés de la grande industrie: Les dessinateurs du Creusot, Formations et carrières (1850–1914)', *Annales: histoire, économie et société*, Vol. 8 (1989), 437–46. And for drawing as a tool to organize the 19th-century machine shop, see James M. Edmonson, *From Mécanicien to Ingénieur: Technical Education and Machine Building in Nineteenth-Century France* (New York: Garland, 1987).
56. Zuboff, op. cit. note 2.
57. Henderson, op. cit. note 2.
58. Desargues quoted in Schneider, op. cit. note 46, 100.
59. Booker, op. cit. note 44, 185–97.

60. A parallel story might be told about the uses and limits of technical drawings by examining the history of Watt's engines, as he moved from free-hand sketches for his own use to his increasingly formalized drawings for production to the fully projective views for the sale and assembly of steam engines abroad in France: see Ken Baynes and Francis Pugh, *The Art of the Engineer* (Woodstock, NY: Overlook Press, 1981), 36–37, 60–69; Jacques Payen, *Capital et machine à vapeur au XVIIIe siècle: Les frères Périer et l'introduction en France de la machine à vapeur de Watt* (Paris: Mouton, 1969).
61. Jean-Baptiste Vaquette de Gribeauval, *Tables de construction des principaux attirails de l'artillerie proposées ou approuvées depuis 1764 jusqu'en 1789* (Paris: n.p., 1792). The 1732 law proclaiming the Vallière system artillery had also been accompanied by official plans and hence had been sanctioned with the force of law: *Ordonnance royale du 7 octobre 1732*, in Pierre Surirey de Saint-Rémy (ed.), *Mémoires d'artillerie, recueillis*, Vol. 3 (Paris: Rollin, 3rd edn, 1745), 450–62.
62. Gaspard Monge, *Description de l'art de fabriquer les canons* (Paris: Imprimerie du Comité de Salut Public, year II [1795–94]). On military secrecy, see SHAT 9a11: Gribeauval to Manson (7 March 1765). On the need for flexibility, see SHAT 4c3/2: Gribeauval, 'Additions et corrections proposées aux *Tables de construction*' (September 1767).
63. SHAT 9a11: Gribeauval to Manson (7 March 1765).
64. One exception is Robert B. Gordon, 'Who Turned the Mechanical Ideal into Mechanical Reality?', *Technology and Culture*, Vol. 29, No. 4 (October 1988), 744–78; see also Gordon and Patrick Malone, *The Texture of Industry: An Archeological View of the Industrialization of North America* (New York: Oxford University Press, 1994), 373–80, 386–88.
65. For an account of the role of tolerances in late-19th-century interchangeable parts production, see Gustave Ply, 'Etude sur l'organisation du service technique dans les manufactures d'armes', *Revue d'artillerie*, Vol. 32 (1888), 344–90; Vol. 33 (1888–89), 5–47, 101–42, 211–43, 297–332. For an account of tolerancing in modern Fordist production, see Earle Buckingham, *Principles of Interchangeable Manufacturing* (New York: The Industrial Press, 2nd edn, 1941), 1–17. For a theoretical account of contemporary computerized tolerances, see Øyvind Bjørke, *Computer-Aided Tolerancing* (New York: ASME Press, 2nd edn, 1989).
66. On gun-making gauges in the early 18th century, see Cesar Fiosconi and Jordam Gusero, trans. Rainier Daehnhardt and W. Keith Neil, *Espiarda Perfeyta, or The Perfect Gun* (London: Sotheby [1718], 1974), 47, 51–55, 195. For calipers and many other guides to machining, see the plates and text of appropriate sections of Diderot's *Encyclopédie*, op. cit. note 26.
67. From the point of view of the shop floor, engineers and managers invariably come to production as outsiders, imposing standards, novel work procedures and new production schedules. Even within a modern firm, relations between employer and employees are in some sense a highly controlled exchange: see Michael Buroway, *Manufacturing Consent: Changes in the Labor Process under Monopoly Capitalism* (Chicago, IL: The University of Chicago Press, 1979), 5–56.
68. Porter, op. cit. note 10.
69. E.P. Thompson, 'Time, Work-Discipline, and Industrial Capitalism', *Past and Present*, Vol. 38 (1967), 56–97.
70. Peter Linebaugh, *The London Hanged: Crime and Civil Society in the Eighteenth Century* (Cambridge: Cambridge University Press, 1992), 371–401.
71. Alder, op. cit. note 24.
72. See any of the standard works on the Gribeauvalist reforms: Pierre Chalmin, 'La querelle des Bleus et des Rouges dans l'artillerie française à la fin du XVIIIe siècle', *Revue d'histoire économique et sociale*, Vol. 46 (1968), 465–505; Howard Rosen, *The Système Gribeauval: A Study of Technological Development and Institutional Change in Eighteenth-Century France* (unpublished PhD dissertation, University of Chicago, 1981); Pierre Nardin, *Gribeauval, Lieutenant-général des armées du roi, 1715–1789* (Paris: La Fondation pour les Etudes de Défense Nationale, 1982).

73. Heinrich Othon von Scheel, *Mémoires d'artillerie contenant l'artillerie nouvelle, ou les changements faits dans l'artillerie française depuis 1765* (Copenhagen: Philibert, 1777), 143–46; Philippe-Charles-Jean-Baptiste Tronson Du Coudray, *L'artillerie nouvelle ou examen des changements faits dans l'artillerie française depuis 1765* (Amsterdam: n.p., 1773), 58. SHAT 9a11: Gribeauval to Manson (7 March 1765).
74. Charles M.S. Dartein, *Traité élémentaire sur les procédés en usage dans les fonderies pour la fabrication des bouches à feu d'artillerie* (Strasbourg: Levrault, 1810), 260.
75. 'Réglement pour la visite, l'épreuve et la réception des canons de fer pour l'artillerie de mer' (1786) and 'Réglement pour la visite, l'épreuve et la réception des canons de bronze pour l'artillerie de terre' (1791), in Monge, op. cit. note 62, 217–25, 226–30.
76. SHAT 9a11: Gribeauval to Manson (7 March 1765). SHAT 4d4: Choiseul to Chateaufer (31 March 1765).
77. Du Coudray, op. cit. note 73, 80.
78. Du Coudray, op. cit. note 73, 66–67. SHAT 4d4: Choiseul to Chateaufer (12 January 1765); Maritz to Choiseul (24 January 1765).
79. Du Coudray, op. cit. note 73, 66. SHAT 4d4: Choiseul to Chateaufer (31 March 1765).
80. Du Coudray, op. cit. note 73, 58, 62; Alder, op. cit. note 24.
81. Wise (ed.), op. cit. note 6.
82. SHAT 9a11: Gribeauval to Manson (7 March 1765).
83. Jean-Louis Lombard, *Traité du mouvement des projectiles* (Dijon: Frantin, year V [1796–97]), xiv.
84. SHAT 9a11: Gribeauval to Ségur (16 April 1783). For a general description of the Klingenthal armoury, see François Bonnefoy, *Les armes de guerre portatives en France du début du règne de Louis XIV à la veille de la Révolution (1660–1789): De l'indépendance à la primauté* (Paris: Libraire de l'Inde, 1991), 287–334.
85. For complaints about the rings in Saint-Etienne, see SHAT T591(1/2): Givry to Fyard (12 February 1783). See also Honoré Blanc, *Mémoire important sur les fabrications des armes de guerre* (Paris: Cellot, 1790).
86. For the artisans' original complaint, see AN T591(1/2): Jean Schmidt *et al.*, 'Aujourd'hui' (29 January 1783). For the government correspondence on this matter, see AN T591(1/2): Givry to Ségur (22 October 1782); Givry to Gribeauval (23 January 1783); Givry, 'Mémoire' (3 February 1783); Gribeauval to Ségur (29 January 1783); Ségur to Gribeauval (11 March 1783).
87. SHAT 9a11: Villeneuve to Gribeauval (4 April 1783).
88. Ibid.; also SHAT T591(1/2): Givry to Agoult (15 March 1783).
89. SHAT Bib. MS175: Comité Militaire (2 April 1783), 3: fol. pp. 194–206.
90. SHAT 9a11: Villeneuve to Gribeauval (4 April 1783).
91. Loc. cit. note 89; also SHAT 9a11: Givry to Ségur (24 April 1783).
92. SHAT Bib. MS175: Comité Militaire (2, 9, 16 & 23 April 1783), 3: fol. pp. 194–206, 222, 234–44.
93. AN T591(1/2): Givry to Villeneuve (22 April & 31 July 1783). AN T591(3): Givry and Bisch, 'Notes de ce que l'on peut tolérer sur les dimensions de la baïonnettes du modèle 1777' (30 January 1784); 'Ordonnance portant règlement' (1 April 1784); Givry to Gau, *fils* (21, 23 August & 22 September 1784); Givry to Ségur (25 August & 17 September 1784); Givry to Gribeauval (1 September 1784); Givry to Gomer (22 September 1784).
94. Alexandre-Théophile Vandermonde, *Procédés de la fabrication des armes blanches* (Paris: Imprimerie de la Département de la Guerre, year II [1793–94]).
95. Alder, op. cit. note 1, 330–40. SHAT 4f7: Sirodin, 'Mémoire sur les proportions dans les armes' (year XIII [1804–05]).
96. William H. Sewell, Jr, *A Rhetoric of Bourgeois Revolution: The Abbé Sieyes and 'What is the Third Estate?'* (Durham, NC: Duke University Press, 1994).
97. Political and religious toleration was one of the central tropes of the Enlightenment, and the literature on the subject is enormous: see note 9.

98. For patents, see Yves Plesseraud and François Savignon, *L'état et l'invention: Histoire des brevets* (Paris: Documentation française, 1986). For the Conservatoire, see Alder, op. cit. note 1, 315–17. For the metric system, see Alder, op. cit. note 24. For the standards of production, see Gail Bossenga, 'La Révolution française et les corporations: Trois examples lillois', *Annales: Economies, sociétés, civilisations*, Vol. 43 (1988), 405–26.
99. Alexandre Vandermonde, 'Economie politique: Programme', in Daniel Nordman (ed.), *L'École normale de l'an III: Leçons d'histoire, de géographie, d'économie politique, Edition annotée des cours de Volney, Buache de La Neuville, Mentelle, et Vandermonde* (Paris: Dunod [1795], 1992); Charles R. Sullivan, 'The First Chair of Political Economy in France: Alexandre Vandermonde and the Principles of Sir James Steuart at the École Normale of the Year III', *French Historical Studies*, Vol. 20 (1997), 635–64. See also Alder, op. cit. note 1, 277, 318.
100. See Eda Kranakis, 'Social Determinants of Engineering Practice: A Comparative View of France and America in the Nineteenth Century', *Social Studies of Science*, Vol. 19, No. 1 (February 1989), 5–70. Each stratum of the hierarchy has been studied: Terry Shinn, *L'École Polytechnique, 1794–1914* (Paris: Presses de la Fondation Nationale des Sciences Politiques, 1980); John Hubbel Weiss, *The Making of Technological Man: The Social Origins of French Engineering Education* (Cambridge, MA: MIT Press, 1982); and Charles R. Day, *Education for the Industrial World: The Écoles d'Arts et Métiers and the Rise of French Industrial Engineering* (Cambridge, MA: MIT Press, 1987).
101. MacKenzie, op. cit. note 3; David Noble, *Forces of Production: A Social History of Industrial Automation* (New York: Knopf, 1984); Zuboff, op. cit. note 2.

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