III

GEOMETRY AND NUMBER AS TECHNICAL INSTRUMENTS IN EARLY MODERN ARCHITECTURE

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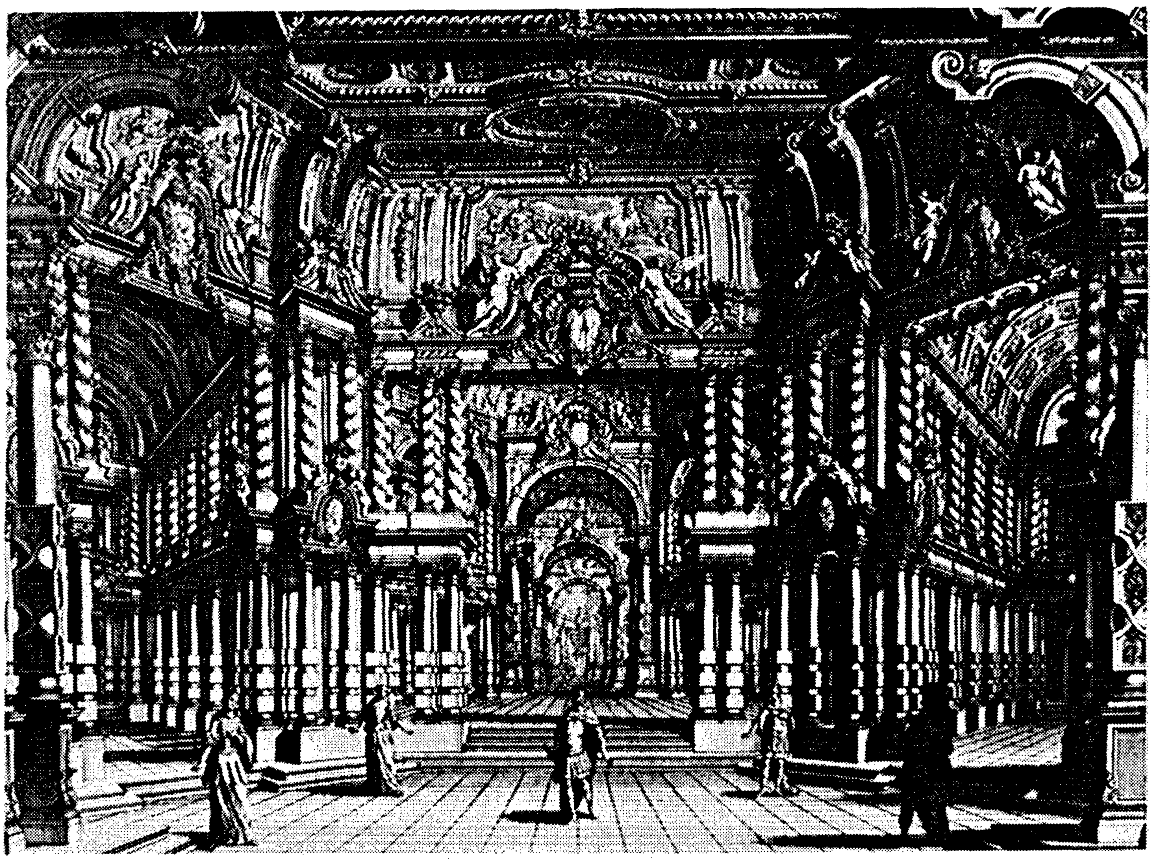
PERSPECTIVE, GARDENING, AND ARCHITECTURAL EDUCATION



In medieval and Renaissance Europe, the order of things and the social hierarchy were prescribed through revelation. The Galilean revolution represented the end of an understanding by which man had always held a privileged position, while at the same time being subordinated to the discipline of the cosmos as a whole. After the seventeenth century, the notion of system, or a whole made of coordinated parts (the prototype of all rationality), was taken from astronomy and utilized as the model for the science and philosophy of the sublunar world.[1]

The epistemological revolution implied a radical transformation of the human condition. Medieval Christianity did not question the inveterate cosmological tradition in which the astral domain was perceived as the prototype of truths and values existing in the sublunar regions. But when the new science rejected the superiority of the heavens, the universe was transformed into a whole comprised of common elements and governed by universal laws. Earth became the "field" of an exact science, as precise as the one that studied the motions of the stars. Modern physics thus originated in the application of exact, immutable notions of an abstract order (*mathemata*) to the sphere of reality.

Modern seventeenth-century philosophy faced for the first time the problem of defining the relation between a perceiving subject and the object of his attention. Man was no longer an integral, nondifferentiated part of the hierarchical totality; he was isolated from the world and other individuals. His attitude vis-à-vis the world had to be modified, and two options were given to him: either dominate and possess the physical universe or effect, through mathematical reason, a new form of reconciliation. The first of these options would become during the early nineteenth century the task of modern technology. It is important to stress that the presupposition of a mathematical structure of reality was impossible to justify ontologically. In order to impose itself, it necessarily had to be proved through experimentation. Hence the importance of clarifying the sources and implications of this presupposition at the earliest stages of modern technological intentionality.

Galileo simultaneously desecrated the heavens and humanized science. He postulated a field of unified knowledge that opposed the ancient hierarchical scheme in which the exactness of the heavens regressed to the confusion of earthly life.[2] By connecting mathematics to experience, Galileo founded modern quantitative science.[3] His overall achievement was much more than a sum of isolated scientific discoveries. He presented to the world a new ideal of intelligibility, one that would eventually encompass the totality of human knowledge. One can discern this as early as 1671 in W. Petty's *Political Arithmetic.* It would be difficult to overestimate Galileo's contribution. The epistemological revolution he ushered in would one day wear the mantle of positivism and, later, scientism.

The new philosophy rejected the texts of Aristotle and instead adopted "the book of nature"; its "text" became the immutable geometrical figures and numbers. Galileo presupposed that the laws of nature were mathematical. Believing that the real incarnated the mathematical, he was incapable of recognizing the distance between geometrical theories and experience. This illusion lay at the heart of all modern quantitative science, particularly of mechanics, which became almost immediately the model for all intellectual endeavours.[4]

The idea of nature, which in antiquity was associated with the idea of life (*physis*), could become an independent entity, and the correspondence between microcosm and macrocosm could be questioned. Thus the notion of a harmonic cosmos, full of anthropomorphic connotations, decipherable by astrology, could be replaced by the transparent universe of astronomy. Motion, once considered a manifestation of life, became a state of material bodies. In the context of a harmonic cosmological order, contemplation was given more value than action; and techniques did not have immanent value. It would have been sacrilegious to imagine that the world, a living and divine being, could be improved by human actions. Consequently, one's intent was never to modify the world's order but rather to discover and celebrate its harmonies. This traditional humility was indeed very difficult to overcome. The fact is that in one way or another, it was perpetuated through Newtonianism and was not subverted until the end of the eighteenth century.[5] But once the tools of physico-mathematical intelligibility were forged, science became the dominant ethos until subsumed by technology during the early nineteenth century.

Modern science implied, therefore, a distance between objects and mind, so that the latter could affirm its right of jurisdiction over the materiality of the former. This relation started to appear during the second half of the sixteenth century in the writings of philosophers, craftsmen, and mathematicians.[6] During the seventeenth century, the idea of dominating the physical world was explicit in the work of Francis Bacon and become a fundamental premise for research at France's Royal Academy of Science and England's Royal Society.[7] In both institutions, technical and experimental investigations held the same importance as scientific speculation. This was indicative of the role assigned to the new epistemology, that is, the joining of the practical and theoretical dimensions of knowledge, transforming the previously contemplative *orbis doctrinae* into an instrument of power.

Implicit in the geometrization of the epistemological universe was the possibility of transforming architectural theory into an instrument for technological domination. This situation, however, as should be evident from previous chapters, was never free of ambiguity. Geometrical science throughout the seventeenth century retained powerful symbolic connotations. Consequently, the use of geometry to modify God's work, that is, the technical actions of man in the world, was frequently shaded with the colors of traditional magic.

Magic and Technique

Bernard Palissy, a well-known craftsman, gardener, and architect, was one of the late-sixteenth-century authors who considered practical knowledge more important than any exclusively theoretical speculation derived from Aristotelian contemplation. He was a fascinating figure who became very popular in Paris between 1575 and 1584 through a series of public lectures illustrated by physical demonstrations and natural objects from his own collection, which included minerals, plants, and animals. Modern biographers have overemphasized the liberal, scientific, and antimedieval spirit of this man who spent long years of his life trying to discover procedures for clay enameling. This rendering of his intentions is simplistic, however.[8]

Palissy was concerned with a variety of themes, all referring essentially to the transformation or configuration of the human world. The first section of his *Recepte Véritable* (1563) is devoted to agriculture and reveals the mythical dimension underlying the conception of a geometrical garden. This symbolic program, to be modified and enriched, remained the basis for the majestic creations of Baroque gardening. It drew its authority from the meaning of Euclidean geometry and its necessary reference to intuition. The book is organized as a dialogue in which the author responds to questions and objections from an imaginary interlocutor. After describing his garden as "the most useful and delightful that has ever been conceived," Palissy explained that his source of inspiration had been Psalm 104, in which a garden was described as a place of refuge for persecuted Christians.[9] Then "confused with admiration" and inspired by the wisdom of the prophet and the good will of God, Palissy "imagined the figure" of a garden whose excellent beauty and ornament corresponded, at least in part, to the biblical description.[10] He declared that it was not his intention simply to emulate his predecessors, who had worked without *theory*. Only those who have "acted correctly according to the order of God" should be imitated. Palissy perceived "so great abuses and ignorance in all the arts" that it seemed all order had been corrupted; laborers worked on the earth with no philosophy, blindly following the routines and customs of their predecessors, ignorant of the "main causes" and nature of agriculture.

Palissy's interlocutor could not believe his ears. What need had a laborer for philosophy? Palissy replied that there was no art in the world that needed so much philosophy as agriculture. Although Saint Paul had warned men against false philosophers, his admonition concerned those thinkers who pretended to attain divine knowledge. Palissy, however, regarded his philosophy not of this speculative kind but rather as a collection of observations derived from experience. Thus Palissy avoided the dangers that, for a traditional order, were implicit in his recognition of the value of technique. Paradoxically, he achieved his objective through an incipient dissociation of the domains of religion and science.

Palissy provided some practical advice, referring to the four traditional Aristotelian elements: air, water, fire, and earth, always conscious of their mythical significance. He then described his garden. The site was to be located near water: a river or a fountain. This also implied the proximity of mountains. After having found such a place, he intended to design a garden of "incomparable ingenuity," the most beautiful under the sky after Eden. First, he would determine the "squaring" of the garden, its width and breadth, in relation to the topography and the location of the source. He would then divide the whole into four equal parts and separate them by great avenues. In the four corners of the crossing, there would be amphitheatres, and at the endings of the avenues and the corners of the perimeter, eight "marvelous cabinets" would be built, all different and "of a kind such as has never been seen before." Palissy stressed that his conception was inspired by Psalm 104, "where the prophet described the excellent and marvelous works of God and, contemplating them, humbled himself in His presence and commanded his soul to praise the Lord."[11]

Each extraordinary cabinet, containing a variety of fountains and mechanical inventions, was described separately. The mysterious iridescence of the enameled surfaces that were to cover the walls and vaults of these grottoes was intended to be their most prominent feature. Palissy seemed fascinated by the reflectiveness of enamel, a property traditionally associated with the symbolic value of gems and precious metals. He managed to achieve the same effect with clay brick through an artificial process and described his accomplishments as true acts of white magic. The different colors, melted by fire, combined to produce evocative figures, while hiding the joints of the brick construction, so that everything appeared as one piece. The walls, polished like precious stones, could be left uncovered, their beautiful surfaces reflecting the fountains and automata. Each cabinet would also exhibit a clearly visible phrase praising human knowledge, emphasizing its transcendent value: for example, "Without wisdom it is impossible to please God," and "Wisdom is our guide to the eternal Kingdom."[12]

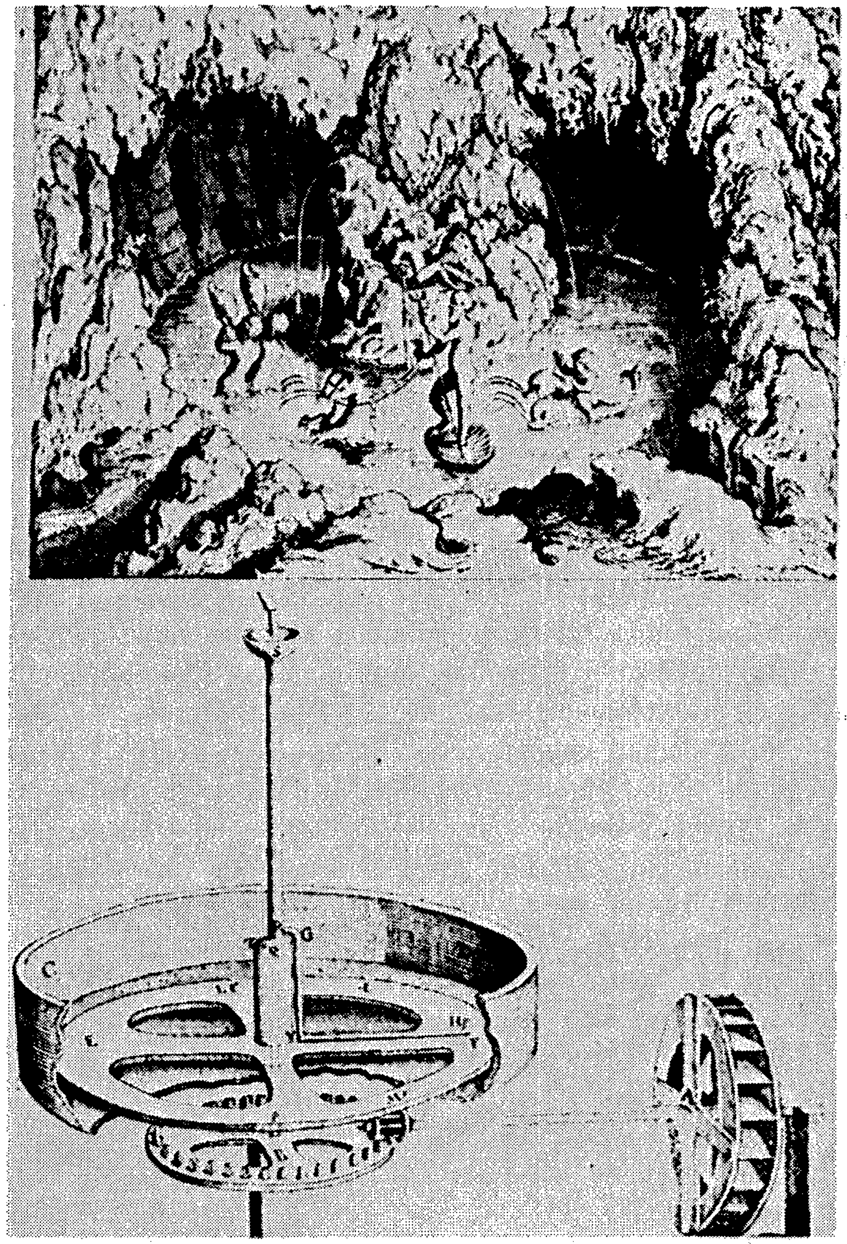
In the mythical universe adhered to by Palissy, his technical interest was totally explicit, and yet his concern was always to establish contact between God and man through the actions of the latter. Accordingly, he devoted himself to the clarification of technical operations. His "philosophy" was meant to guide human action, but only within the established order. Scientific knowledge, that is, geometry, mechanics, and alchemy, was motivated by reconciliatory objectives. Palissy's geometry and mechanics dominated nature, an early declaration of their autonomy from theological speculation. In the end, however, this domination was a form of magic, and the empirical philosophy of agriculture drew meaning from its own power of transcendence.

It is interesting to note that Palissy's attitude actually led him to anticipate some of the principles of eighteenth-century architectural theory. For example, the cabinets at the ends of both avenues were to be completely natural. Branches of trees would constitute architraves, friezes, and pediments, while the trunks would act as columns. The interlocutor of the *Recepte Véritable* pointed out that all famous architects had provided fixed proportions for their buildings and questioned Palissy's solution with the fact that the proportions of the cabinets would have to change with the growth of the trees. The answer was simply that the model was better than any copies. Palissy maintained that the architects of antiquity had copied in stone the forms of trees and the human body, and therefore the "columns of the First Architect" had priority. The bases and capitals were to be formed by making incisions and allowing the sap to harden. The growth of the branches would be controlled through "geometry and architectural rules."

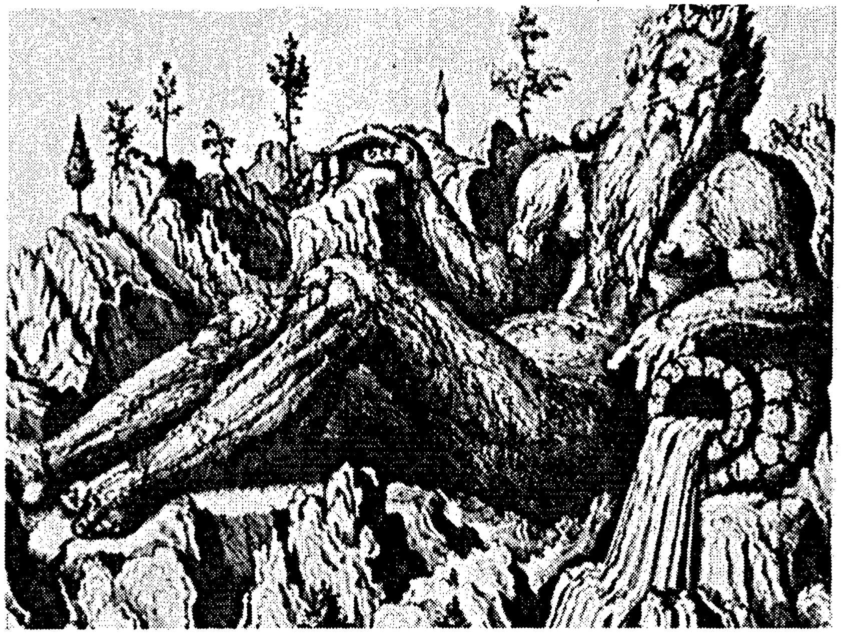
Palissy was frequently accused of sorcery. In the eyes of his contemporaries, he possessed certain recipes that allowed him to control nature. His technical operations were still viewed as tampering with God's order at a time when the line between white magic and black magic was becoming increasingly more difficult to draw. (Intoxicated by his freedom from religious determinism, man would eventually transform black magic into technology.) But the mechanical arts, which had been given a new status during the early modern era, particularly architecture and gardening, were intended as white, reconciliatory magic; Palissy's primitive natural philosophy was only a means of showing respect and following God's will in the best possible way.

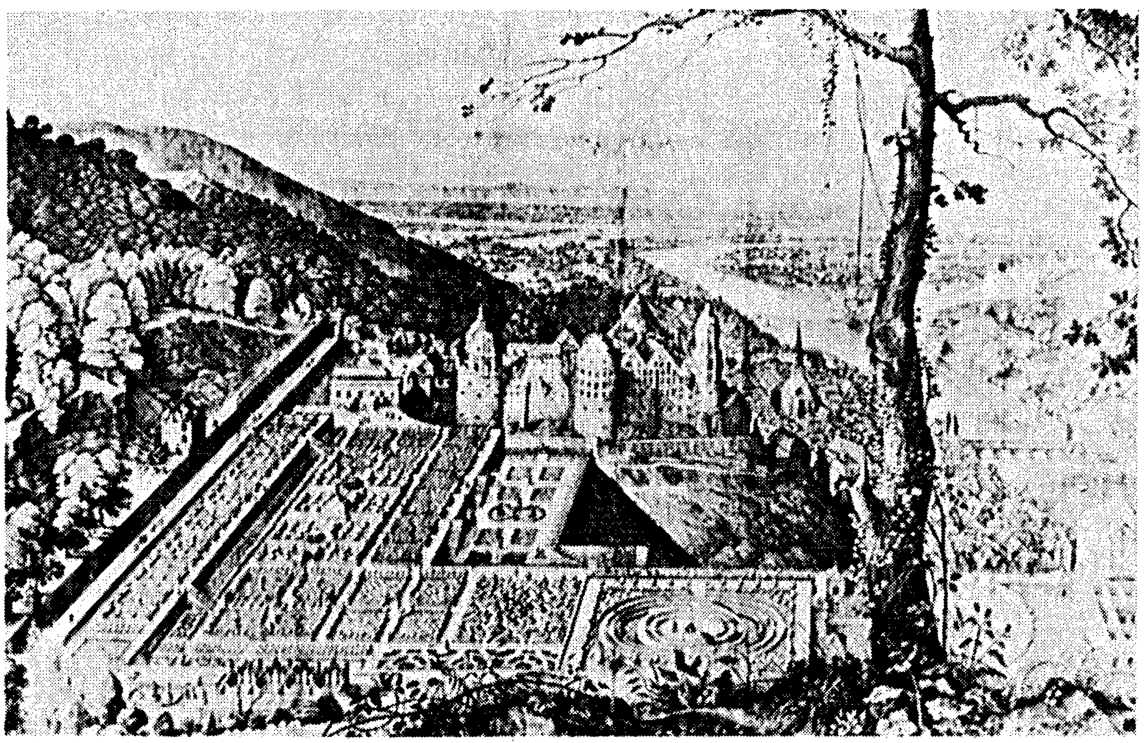
During the first half of the seventeenth century, the meaning of *techné* was not substantially modified. An excellent testimonial to this is provided by the writings of Salomon de Caus, a brilliant gardener and mathematician with interests in mechanics, architecture, music, and anamorphosis. His *Les Raisons des Forces Mouvantes* (1615) is basically a collection of illustrations that, apart from a few elementary machines, such as levers, pulleys, and gears, demonstrate the workings of marvelous fountains and complex automata invented by the author. De Caus did not distinguish between toys and useful machines. Moreover, he was interested particularly in those machines that embellished his gardens and inspired awe and fascination. His work also included garden designs that combined anthropomorphic and geometrical schemes. As with Palissy, the act of giving form to nature was for De Caus a meaningful *poesis.*[13]

In the preface of *La Perspective avec la Raison des Ombres et Miroirs* (1612), De Caus proposes to produce a useful work for architects, engineers, and painters, as well as to enjoy the pleasures of speculation. He was very interested in perspective, believing that it was the only "part of mathematics" capable of providing pleasure to the sight.[14] The first attempts to structure a mathematical theory of perspective date back to the last two decades of the sixteenth century. Mathematicians such as Federico Com-



Design for a grotto of Neptune, showing the mechanism of the fountain, from Salomon de Caus's *Raisons des Forces Mouvantes.*





Anthropomorphic garden, design by Salomon de Caus, from his *Raisons des Forces Mouvantes.*

The garden of Heidelberg Castle as originally designed by Salomon des Caus, from his *Hortus Palatinus* (1620).

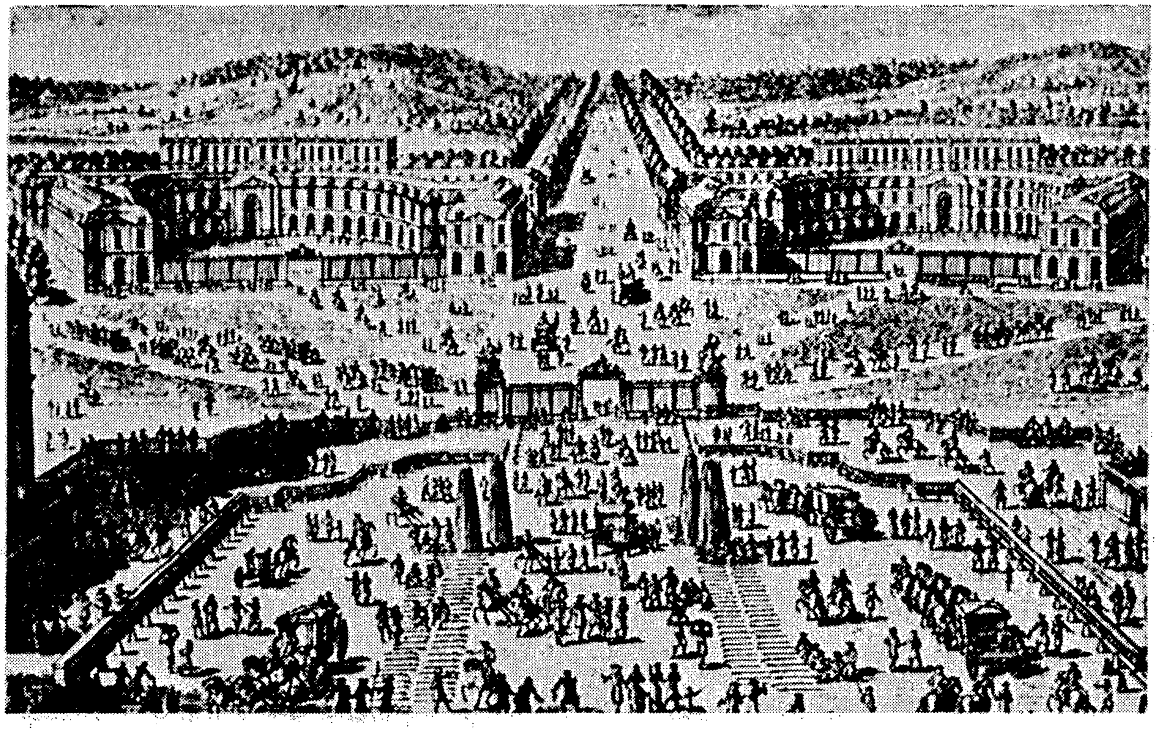
mandino, Simon Stevin of Bruges, and Guido Ubaldo del Monte wrote texts of great complexity, which were impossible to apply in practice. Only during the seventeenth century did the use of methods of *perspectiva artificialis* become truly popular with artists.[15]

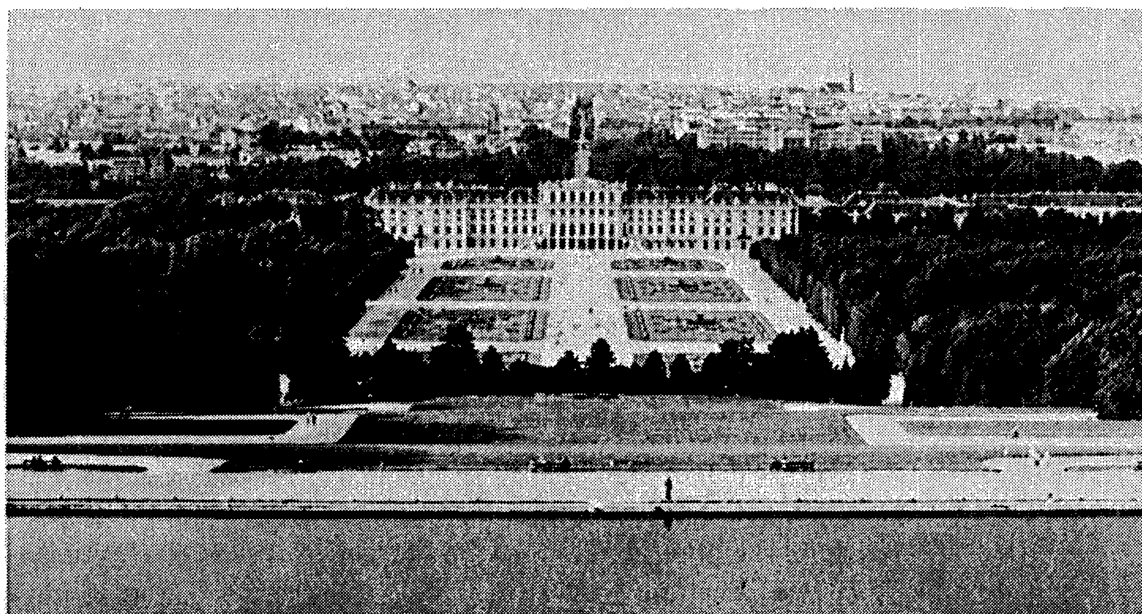
The problem of perspective is not easily reducible. Perspective became strictly possible only when man began to view himself as a subject and external reality as a collection of objects. The development of perspective theory is intimately connected with the epistemological revolution and, associated with this revolution, the fundamental dissociation between man and world, between body and mind. Cartesian philosophy postulated perspective as a model for human knowledge. But it was not until the nineteenth century that perspectivism became a true form of subjectivism and was adopted as a universal prototype of knowledge. Only then did man actually believe in the isolation of his mind from other minds and the world, thereby rejecting the fundamental intersubjective reality given to embodied perception. And this, of course, led him to accept no objectivity other than the evidence of mathematical logic. Even today it is difficult to admit that our embodied perception of the world is not equivalent to perspective representation. The images of the photographic camera are taken to be the only true representation of reality.[16] Perspective, of course, is only one way of seeing, corresponding initially to Cartesianism and implying the imposition of a geometrical scheme on reality in order to establish a relation between *res cogitans* and *res extensa*.

During the seventeenth century, art, gardening, and architecture—disciplines responsible for the configuration of man's world—were necessarily concerned with the fundamental problem of philosophy; the reconciliation between subject and object. In order to endorse the meaning of human life, the arts had to confirm mankind's relation to the sphere of absolute values. Hence the use of perspective as an ideal organization of external reality. The transformation of cities, gardens, and internal spaces implicitly demonstrated the belief in the transcendent nature of the new geometrical knowledge. But Baroque perspective, in marked contrast to nineteenth-century perspectivism, was a symbolic configuration, which allowed reality to keep the qualities of traditional perception in an essentially Aristotelian world. The great vistas at Versailles are not equivalent to Haussmann's boulevards. Although by its very nature a geometrical operation, perspective made it possible for seventeenth-century artists to transform their physical environment into a symbolic reality. In this way, it also embodied a symbolic operation that, perceived through sensuous experience, evoked ideal truth and excellence. In seventeenth-century Versailles, color, smell, light, water games, fireworks, and, indeed, the full richness of mythology played a major role. The meaning of the place as the seat of government and the dwelling of the Sun King derived from a synthesis of the power of geometry and its potential to enhance sensuality. The intention was not to express "absolute domination" but rather to make manifest a truly human order.

The theory of perspective could very readily abandon its intimate ties to perceived reality to become pure geometry. This became apparent in the examination of Desargues's work (see chapter 3), which, because it was so exceptional in its disregard of traditional practice and symbolism, was rejected by artists. As a rule, however, the architects of the seventeenth century managed to synthesize the dimensions of qualitative, preconceptual spatiality and geometrical conceptual space. Since *spatium mundanum* was identified with the *ens rationis* of geometry, the possibility of a conceptual space appeared for the first time in the sciences and the arts. But Baroque space also retained its qualities, its character as place. It was always a *plenum*, never an odorless or colorless vacuum. The infinity and geometrical characteristics of Baroque space required the sensual qualities of materials and their plastic representation. Baroque architecture emphasized the presence of space in the world of man, reestablishing a meaningful relation between the subject and external reality.

Baroque architecture conveyed the almost tactile presence of a space filled with life and light, with angels and mythological figures. This contrasted vividly with the empty and homogeneous spaces suggested by Boullée and Ledoux. Descartes, Galileo, and Leibniz rejected the existence of the vacuum. Descartes even recognized a difference between the *indéfinition* of geometrical human space and infinity, which was the exclusive attribute of God.[17] Perspective only made visible the geometrical infinity in the world of man. This was, in effect, a pregnant infinity, full of symbolic connotations, which established a hierarchy with reference to the temporal power of the king or the spiritual power of the church. The paradigm of the seventeenth century was to allow infinity to appear *in reality*. The late eighteenth century, on the other hand, wished to create a new nature in which the infinite and eternal void would be evident.

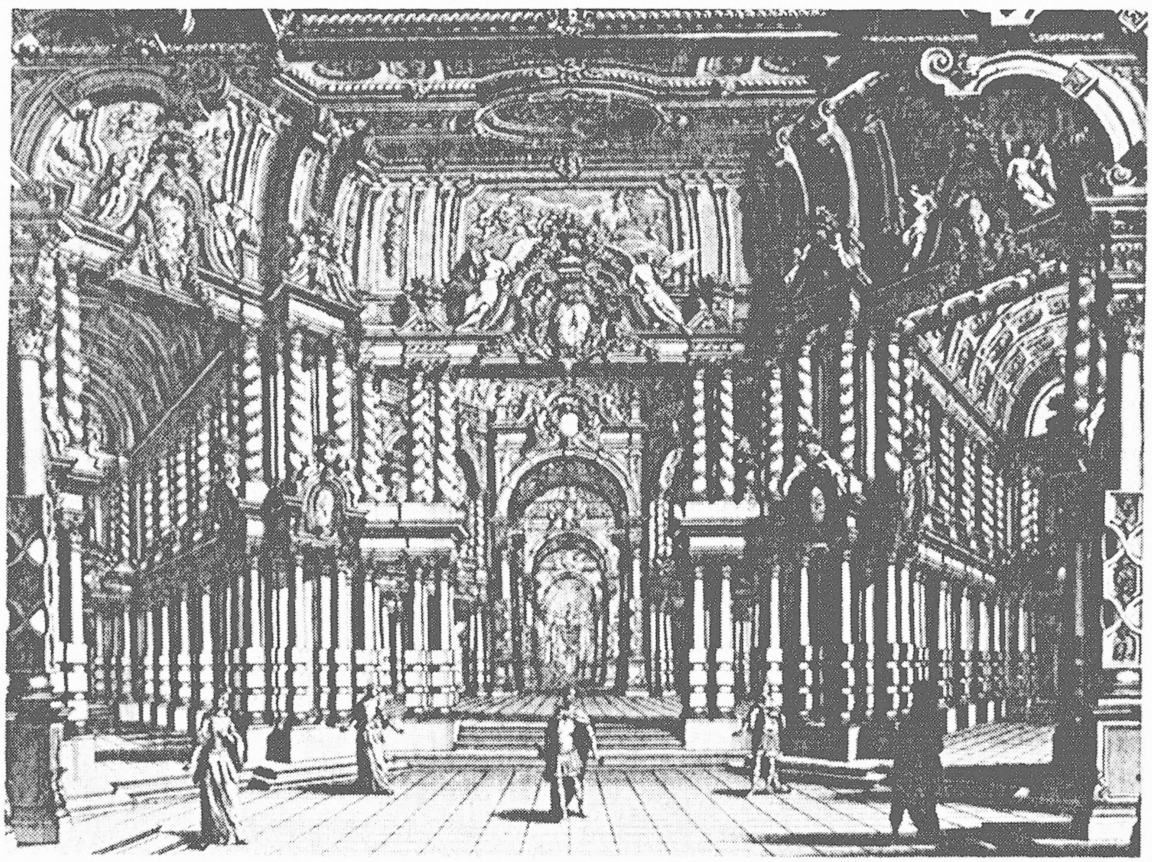




Perspective view of the stables and the courtyard of Versailles. Engraving of the view from the palace by Pérelle.

View of Schönbrun Palace and Vienna in the background, from the *gloriette* in the garden. Project by J. B. Fischer von Erlach and Ferdinand von Hohenberg.

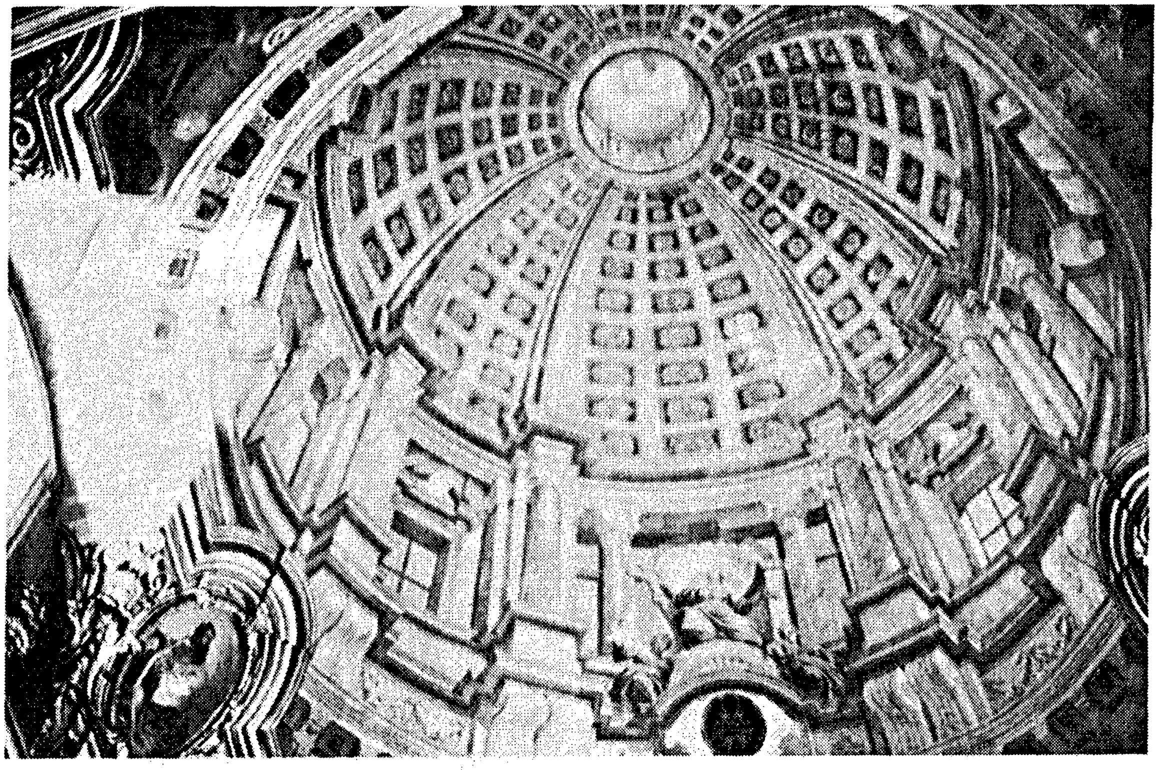
Stage-set design by G. Galli-Bibiena, from his *Architetture e Prospettive* (1740).



The theory of perspective allowed man to control and dominate his external, physical reality. Like other mechanical techniques in their implementation of mathematics, however, this formal control of the traditional hierarchy of qualitative places by the rules of geometrical perspective was always an act of reconciliation. The famous frescoes of *quadratturisti* like Andrea Pozzo were supposed to be seen from one predetermined point of view, permanently marked on the pavement of a church. This revealed a true hierarchical and transcendental vision that appeared only when man occupied his place in the geometrical structure of the Creation. Another type of perspective projection, anamorphosis, involved the *distortion* of the reality it represented. Here a geometrical theory clearly dominated and subjected normal perception to its own wishes by placing the point of view in unexpected places, generally on the surface of the drawing or painting.[18] These "tricks" revealed the artificial character of perspective and showed the extent to which theory could become autonomous and control practice. Although these projections had been used sporadically during the late Renaissance,[19] they became extremely popular during the first half of the seventeenth century, when the theory of anamorphosis was being written. Once it had been clearly formulated, it became a scientific curiosity, a form that could be imposed on any content. Reality as presence and reality as appearance were not only intentionally disjointed, but the primacy of undistorted presence was replaced by the primacy of distorted appearance.[20]

During the earlier part of the century, however, anamorphosis had other connotations. The architect J. F. Niceron devoted a whole book to the study of this "curious perspective or artificial magic of marvelous effects."[21] His *Perspective Curieuse* (1638) employs the tone of a scientific work but develops in an atmosphere of fantasy and myth. Niceron understood the importance of applied mathematics and praised Archimedes for having reputedly used this science in the resolution of technical problems. He believed that mathematics possessed many wonderful qualities. It provided the means for the execution of projects, was useful for the delight and recreation of our senses, established rules of order and symmetry in architecture, and indicated how to build machines.

Niceron rejected all "useless speculation." His theory seemed to be concerned only with mathematics as it applied to the transformation of reality. The results of this application had, in his view, a *miraculous* character. And perspective was important be-



View of the vault in the *Jesuitenkirche* of Vienna. The dome is a fresco by Andrea Pozzo, an example of the *quadrattura* method.

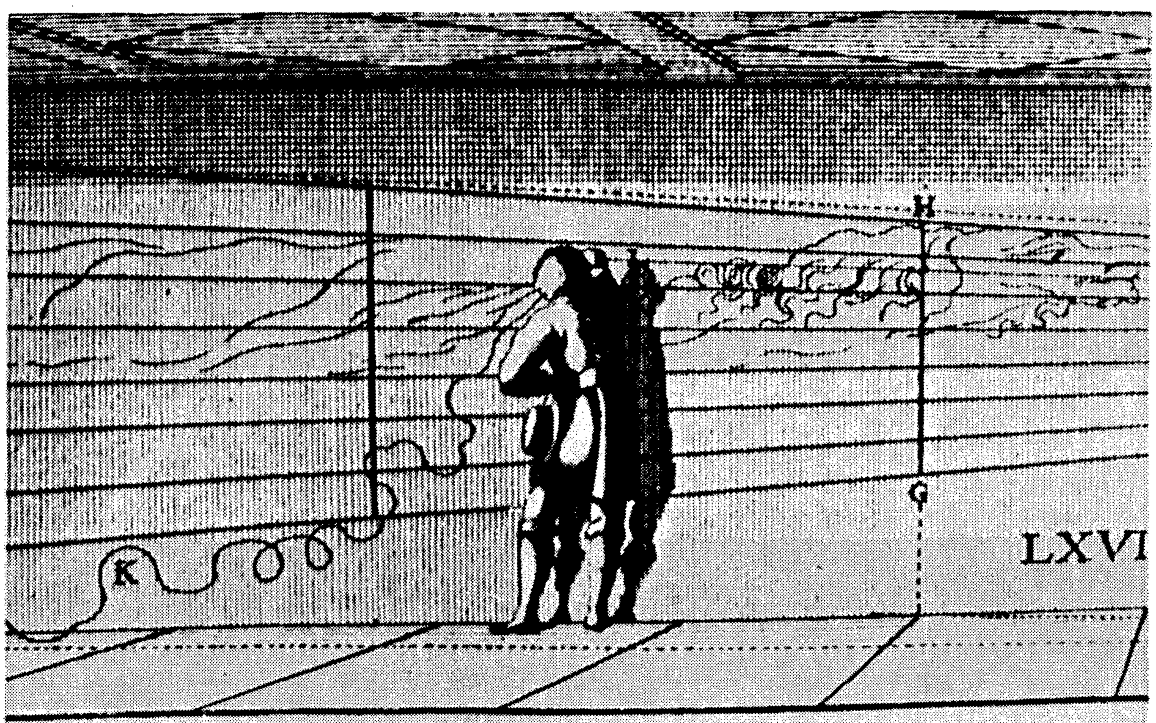
Jean-François Niceron, engraving by Michel Lasne, showing S. Trinità dei Monti in the background, from *Thaumaturgus Opticus* (1646).

cause it was identified with the "miraculous productions" of mechanics, hydraulics, and pneumatics. It was his opinion that perspective was indispensable to architecture, lending to it order and symmetry.[22] Explaining the title of his work, he wrote that "curious perspectives" were not only useful, like normal perspective, but delightful as well. Calling it artificial magic did not imply any illicit practice or communication with "the enemies of our health." In fact, "natural magic" was not only permissible but constituted the "optimal degree of perfection of all sciences."[23] Niceron identified magic with the technical inventions that had their origin in mathematical science. The beautiful and marvelous effects of "the sphere of Poseidonius," which explained the configuration of the heavens; Archimedes's mirrors and war machines; and the "automata of Daedalus" were to him the highest examples of art and industry. Thus "true magic or the perfection of the sciences consists in perspective, allowing us to know and discern more perfectly the beautiful works of nature and art."[24]

The dual nature of Baroque perspective is evident in Niceron's work. By geometrizing the world, man gained access to the truth. Perspective both revealed the truth of reality and reflected man's power to modify it; that is, it was a form of magic. It is significant that the more ambitious applications of anamorphosis to fresco painting appeared in the convents of the Minimes, where some of the most advanced ideas of the time were being discussed. This was the order entered by Niceron and also by M. Mersenne, the well-known author of a treatise on universal harmony, whose letters provided an important link among scientists and philosophers of the early seventeenth century.

In the epistemological framework of the first half of the seventeenth century, technical action could never be free from magic or symbolism. This is attested to by the various texts written at the time, which addressed the transformation of human reality. Due to the nonspecialized character of the traditional epistemological universe, this transformation, in any of its forms, was always relevant to architecture. It should come as no surprise, then, to note the great interest architects had in fireworks and other similar machines "for war and recreation"[25] or their concern for ephemeral structures, like canvas triumphal arches, facades, and perspective stage designs framing processions and state or religious celebrations: transformations that sought to realize the symbolic potential of public space.

In 1652 C. Mollet published a book on astrology and *Theatre des Plans et Jardinages*, a treatise on gardening.[26] After some prac-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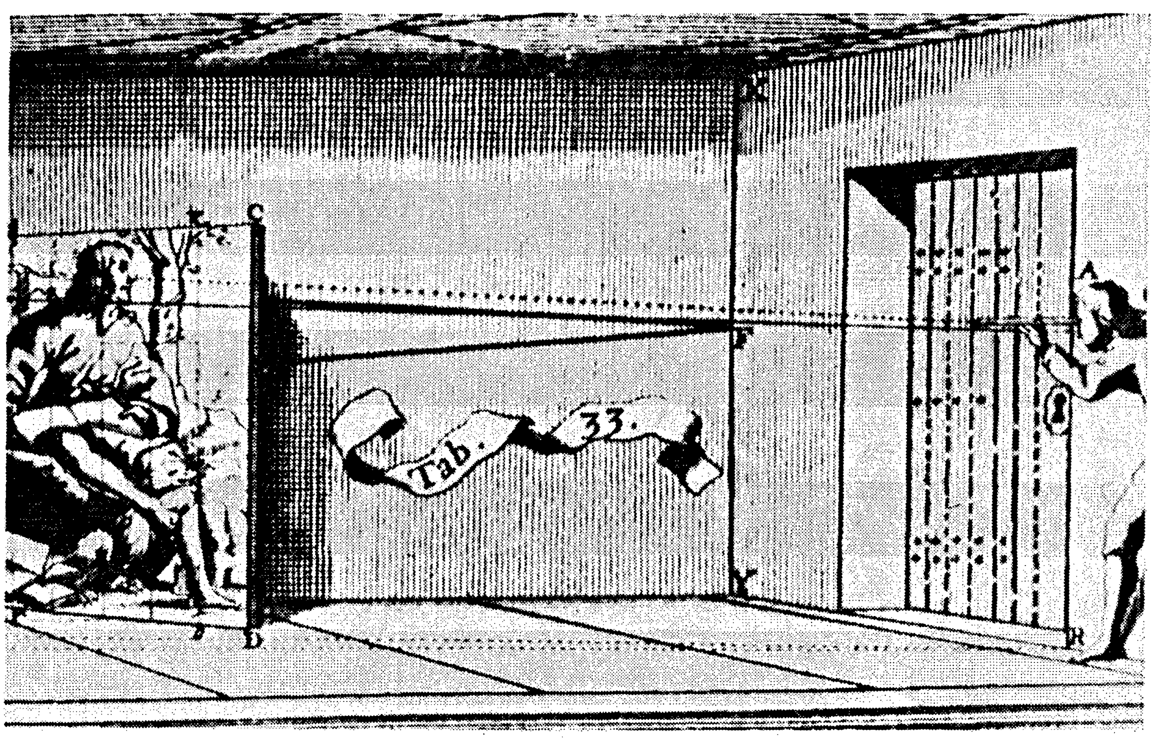
John the Apostle at Patmos. Details from the execution method of a fresco in anamorphosis by Niceron. Works like this, executed in the monasteries of the Minimes at Rome and Paris, would be intelligible when viewed close to the wall plane, but hidden in conventional frontal perception. Illustration from *Thaumaturgus Opticus.*



tical advice, Mollet described the Aristotelian heavenly spheres and showed how to avoid evil influences from the stars. *Praxis,* for Mollet, was intimately linked to the conceptions of a hierarchical and animistic cosmos. Reality was perceived as the place where man was in close contact with God. The gardener's life thus follows the pattern of cosmic time: praying to God in the mornings, living the day in peaceful harmony, and receiving His blessing every evening. Mollet thought that this was the incorruptible model to be followed by young people seeking knowledge in gardening.

Stipulating a similar universe, J. Boyceau's *Traité du Jardinage* (1638) describes the four Aristotelian elements as a reconciliation of opposites.[27] Boyceau declared that the earth had been placed by God in the center of the universe, receiving from Him the power to beget and support life. The gardener should have some technical knowledge, including geometry, arithmetic, architecture, and mechanics. But ultimately, the traditional *poesis* of gardening, which connects man to the earth (his womb and sepulchre), was the dominant theme. Gardening and agriculture still did not take place in a universe of precision. Its object was never merely to dominate nature or to increase the productivity of crops.

After the seventeenth century, God began to retire from the world. This was an unavoidable consequence of the epistemological revolution and the generalization of mechanistic intelligibility.[28] In 1693 B. Bekker published an important work that shows the great transformation that had occurred between the seventeenth century and the Enlightenment. *The Enchanted World,* described the substitution of supernatural revelation by nature. Bekker did not stop at revealed truth. Since God had given man reason, it should be used in our interpretation of the Bible. Sacred authority could be criticized through the natural knowledge of God that man possessed. Bekker expelled angels and demons from the world, and miracles and sorcery he considered illusions. God was now revealed through the still inexplicable marvels of nature, open to the perceptions of the enlightened man.

During the eighteenth century, craftsmen still operated with care; they respected the natural order and were conscious of the transcendent humility of action. The sacred nature of reality did not encourage mindless exploitation. Throughout the century, there was a genuine fascination with technical achievements that reproduced the wonders of nature. For example, C. C. Scaletti, in his *Scuola Mecanico-Speculativo-Practica* (1711), extolled mathematics as the true cause of mechanical, hydraulic, and optical phenomena.[29] He rejected explanations based on "occult qualities" and adopted an experimental method. Nonetheless, he described the operator of "practical mechanics" as a magician with miraculous powers. Instead of concentrating on pragmatic applications of mechanics, he was more interested in describing such marvelous toys as a walking silver cup or a mechanical fly that had belonged to Charles V. And the architect Pierre Patte listed, among the other arts and sciences that had advanced significantly during the reign of Louis XV, the manufacture of automata.[30] He was especially impressed by the mechanical flutist five and a half feet tall designed and built by Vaucanson.

It is unquestionable, however, that toward the end of the seventeenth century and coinciding with the cultural transformations represented by Bekker's work, occult qualities were removed from technical operations. The foundation of the academies, which replaced the traditional guilds, and the institutionalizing of the *Corps du Génie Militaire* and the *Corps des Ponts et Chaussées*, were events indicative of this first exorcism of *techné*.

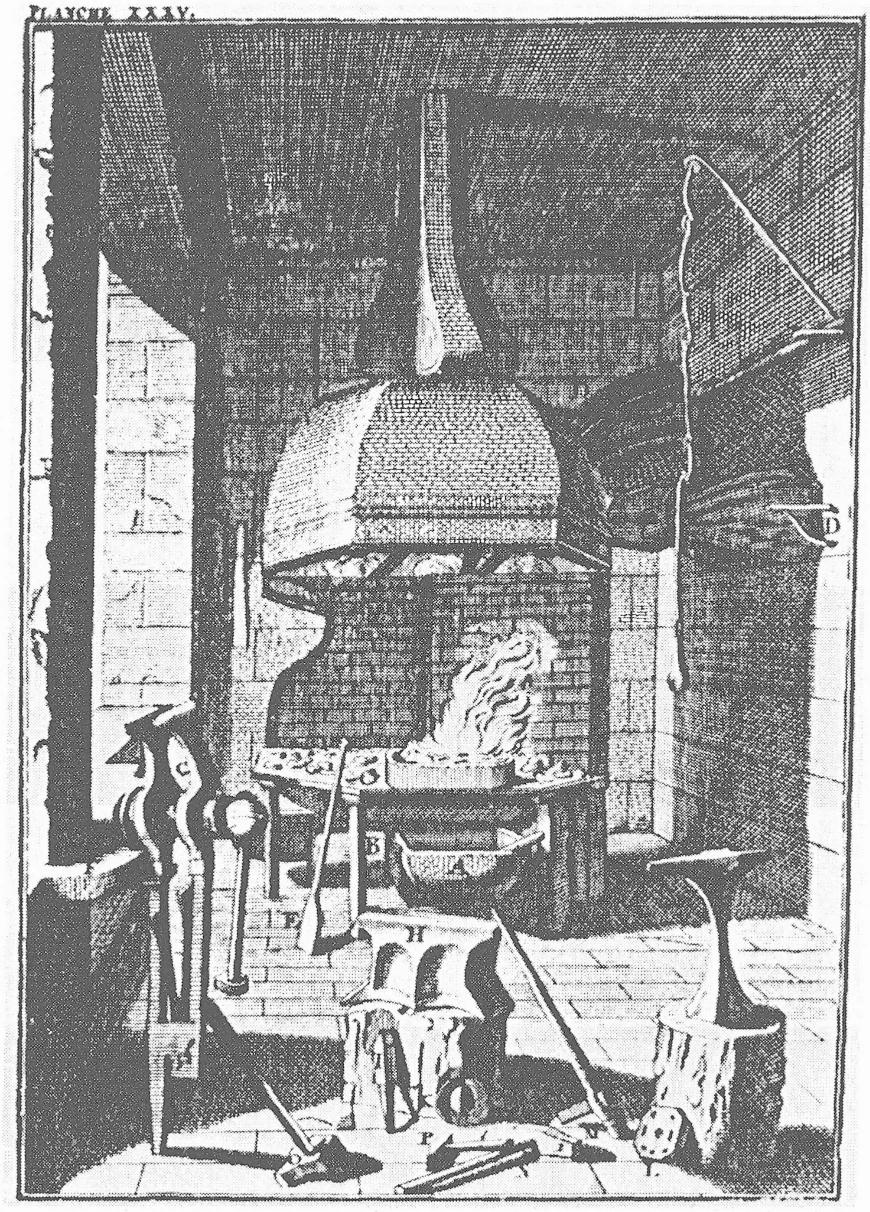
In his role as *historiographe des bâtimens du Roi*, André Felibien attended the first deliberations of the Royal Academy of Architecture. He was also appointed *inspecteur du devis*, and was in charge of reviewing and approving the designs for the roads and bridges of France. In his *Des Principes de l'Architecture, de la Sculpture, de la Peinture* (1699), his interest was mainly linguistic. He was concerned with the prevailing confusion of concepts and names given to tools or elements, and his work was an attempt to define the parts and instruments of the different arts and crafts.

In his section on architecture, he praised Perrault's translation of Vitruvius and then pointed out that his own intention was not to write another treatise. He noted that there were a great number of existing books on the orders, but only a few authors like Philibert de l'Orme, Derand, Desargues, Jousse de la Fleche, and Bosse said anything about stone- and woodcutting or the trades of locksmith and engraver. Felibien believed that these few attempts to elucidate the techniques of architecture did not present a complete theoretical discussion. He was convinced that technique was a most important aspect of architecture and wrote his *Principes* to explain the techniques and tools of the trades: masonry, carpentry, plumbing, windowmaking, blacksmithing, locksmithing, and so forth. He maintained that it was important to have direct contact with craftsmen, to visit their workshops and to examine their machines. But it was at this point that he began to encounter problems. He could not find "reasonable" workers: These "ignorant and strange people" pretended not to know what he was talking about; they "invented ridiculous stories" and hid the most common utensils.[31] The tension between traditional craftsmanship (with its secrets and mythical frame of reference) and the new scientific attitude of academic architects and engineers could hardly be more explicit. This tension only ended after the Industrial Revolution, when the transformation of the long-established relation of production actually took place. Felibien's new attitude to technical operations is nevertheless revealing. He associated his work directly with the academy, presenting it as the result of a common enterprise that reflected the interest of the most distinguished European architects.[32]

Intellectuals of the late seventeenth century also manifested interest in technical and practical problems. John Locke declared a preference for practical knowledge over the manipulation of abstractions in *De Arte Medica*.[33] Leibniz believed it was important to describe the procedures employed by technicians and craftsmen, a task made necessary and possible because "practice is only a more particular and compounded theory."[34] The traditional values of intellectual contemplation, still present in the Baroque period, were superseded in the eighteenth century by values derived from human action and man's eagerness to transform the world. In his article on art for the *Encyclopédie*, Diderot complained about the "harmful consequences" resulting from the traditional distinction between liberal and mechanical arts, which had produced great numbers of vain and useless intellectuals.[35]

The Galilean revolution continued into the eighteenth century in the guise of axiological reform,[36] and the cosmic reason of the seventeenth century became truly human. Once the a priori universality of reason was questioned, human rationality became a pressing invitation to action; the systematization of knowledge was deemed indispensable. Renouncing contemplation for its own sake, Enlightened reason strove to join technical theory with practice, and was often frustrated by the failures of the former to influence the latter.

These transformations are apparent in eighteenth-century treatises on gardening and differ markedly from the ideas expressed in the works of Mollet and Boyceau. Batty Langley, who recommended the "non-stiff" type of garden in his *New Principles of Gardening* (1728), criticized the "abominable mathematical regularity" of some French gardens. His own method, however, also took as its starting point a detailed exposition of geometrical rules.



The blacksmith's workshop, from Felibien's *Des Principes de l'Architecture.*

But it should be obvious by now that this is not a real paradox. For although Langley considered this science "the basis of any layout,"[37] he was not capable of understanding the symbolic implications of a geometry that imposed its form on nature in the manner of the Baroque gardens. For Langley, geometry was a tool, albeit one of great importance.[38] When applied to gardening, geometry was supposed to reproduce the way in which nature itself "strikes with astonishment upon man," surprising him with unexpected "Harmonious Objects."

In 1711 A. J. Dezalliers d'Argenville published his *Théorie et Pratique du Jardinage.* Although it comes rather late in the Baroque period, it represents the first and last systematic exposition of the principles of French Baroque gardens. This is in itself significant. The geometry of the seventeenth-century garden hardly needed elucidation; its symbolic horizon was totally transparent. Dezalliers already cautioned against the use of extravagant features, pointing out that a garden should derive from nature more than from art. He thought it incorrect to sacrifice variety for symmetry.[39] He included general rules, methods, and proportions and added a section on practice, "which is but a consequence of the certainties of theory." This, he thought, had never been previously provided to the public. The description of practice contained instructions on tracing all sorts of figures using geometrical methods, both on paper and in the field.

Dezalliers was conscious of the fact that to trace a layout on the field, actual experience and continuous practice was more important than "profound science." He nevertheless insisted on the importance of his prescriptive methods. The gardener should be able to produce scaled drawings, and Dezalliers provided step-by-step instructions for this craft. In contrast to seventeenth-century texts, his theoretical discourse is a mere *ars fabricandi,* lacking references to the transcendent justifications of technical action. It is significant that in this late work, the geometry of the Baroque garden is already identified with the practical geometry of the surveyor.

Later in the century, as might be expected, natural philosophy exerted its influence on gardening. The two volumes by R. Schabol, *La Pratique du Jardinage* and *La Théorie du Jardinage,* published posthumously in 1770 and 1771, bear witness to this. Schabol believed that gardening was the most noble part of agriculture[40] and that the gardener always "reflects on what he is to do and never acts without a method founded on rules and principles."[41]

Nor should he fail to consult Nature if he desires to be in harmony with it. Moreover, the gardener is likened to the astronomer, as one who observes phenomena in order to fully comprehend them: "The gardener . . . contemplates Nature in the dark sanctuary of the earth's womb, or in the mechanism of plants."[42] Consequently, Schabol rejected speculative methods and contended that "experimental and instrumental physics" were indispensable for the clarification of phenomena in nature. He realized that nature often confronted man with insurmountable difficulties and enigmas and that the diversity of phenomena was often astounding and disconcerting—thereby forcing man to accept the humility of his intelligence. In spite of this, Schabol believed he could explain some of the "effects" he had observed in plants. It was not a matter of presenting solutions or demonstrations but of suggesting "probabilities founded on conjectures and presumptions derived from facts."[43]

Thus nature, while retaining its evocative mysteries, became a book open to scientific discovery. Schabol, for example, could not understand why plants and animals, composed of internal parts whose "functions" were very similar, were nevertheless very different. In view of all that remained mysterious, the gardener should simply admire and follow the laws of the "Author of Nature," whose will hides from us the causes. But because God had attributed "particular actions" to each one of the different species of plants in the Creation, the gardener should not be discouraged. He should always respect and praise the Lord's design.

Schabol's work thus demonstrates the epistemological humility of the eighteenth century. His understanding of *mathemata* contrasts sharply with that of nineteenth-century biology, for which the identity of functions and structural similarities became the dominant feature, leading eventually to a godless theory of evolution and providing a formal model of classification that had a deep and long-lasting influence on architectural history and theory.[44] Schabol, however, also believed that theory, understood as a technical set of rules, should be applied to practice in order to increase production. In his *Théorie*, he complained because primitive intuitive methods were still being used. Earlier authors had not combined experimental physics with a knowledge of the mechanism of plants, but Schabol thought this union was essential: "Theory and practice need one another; their success depends on their correspondence."[45]

This ambiguity was present in all technical disciplines during the Enlightenment since practice retained its traditional character. Building techniques, in particular, did not change much. Around midcentury, the famous engineer Jean-Rodolphe Perronet received some rather striking reports about the talents and abilities of members of the *Corps des Ponts et Chaussées*, the most distinguished civil engineers in Europe: Picard, for example, knew practically no geometry, mechanics, or hydraulics; he had some idea about mensuration but encountered great difficulties determining cost estimates or architectural details. Also, he had no education and found it difficult to design, to read, or to do mathematics.[46] At Soissons, the engineer Loyseau confessed that science, art, and architecture were as foreign to builders as Greek.

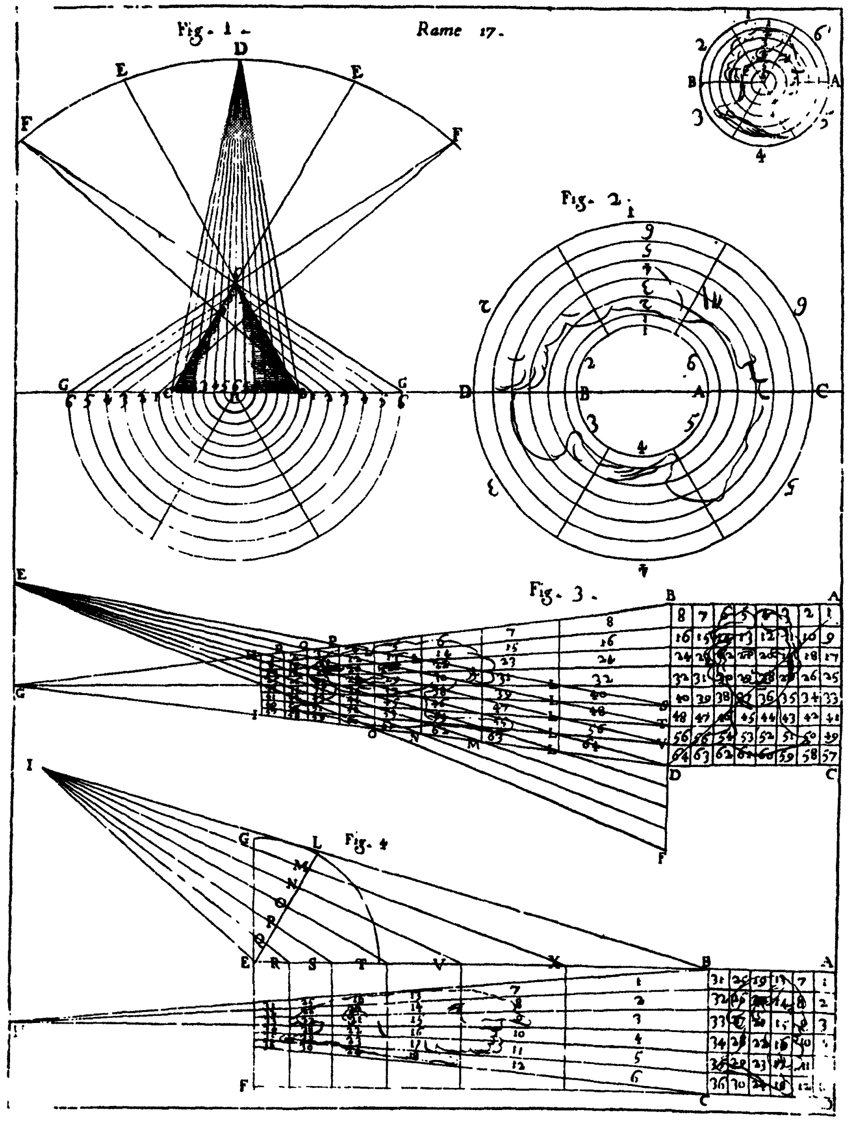
Transformations in theory of perspective also revealed the exorcism of the technical dimension. Around the middle of the seventeenth century, there was a famous dispute between Desargues and Du Breuil concerning the significance of anamorphosis. In 1653 Bosse published a work entitled *Moyen Universelle de Pratiquer la Perspective sur les Tableaux ou Surfaces Irregulières*, a treatise that examined all sorts of strange projections. In contrast to the traditional implications of these "tricks," which were generally recognized in the early seventeenth century and appeared in Niceron's work, Bosse emphasized the universality and simplicity of his methods while ignoring the qualitative difference between normal perspective and distortions. He made no allusion to occult or magical characteristics; to him any projection was merely the result of applying a common set of geometrical rules.

In his *Manière Universelle pour Pratiquer la Perspective* (1648), Desargues showed a precocious prototechnological turn of mind. He unequivocally declared his dislike for studying and doing research in physics or geometry "unless these sciences prove truly useful to the intellect" and can be "reduced" to effective action.[47] Thus the same author who discovered the theoretical principles of projective geometry[48] and who took the first step toward a true functionalization of reality also denied the value of speculative geometry unless it became an effective technique for practice in all the arts.

Toward the end of the seventeenth century, the mathematician Ozanam also wrote about anamorphosis as a simple scientific curiosity.[49] In his work on perspective, Ozanam denied the magical or symbolic attributes of perspective, emphasizing that this art simply represented visible objects as they appeared to the human eye.[50] This is the conception of perspective, popularized initially by Andrea Pozzo's treatise, that would become common in the eighteenth century. It is significant that the closest identification between perspective, architecture, and stage design also occurred around this time in Ferdinando Galli-Bibiena's *Architettura Civile* (1711). This work touched upon geometry and mechanics, whose synthesis was epitomized by Bibiena's own "invention," the *scena per angolo*. In this method of stage design, the introduction of oblique vanishing points created an impression of reality that had not been possible using only one-point perspectives. The identification of the stage and the city was also evident in the customs and dress of the eighteenth century, especially in Paris.[51] The city became a stage for the play-acting of roles, that is, the representation of individuals' stations in life. In a world where the absolute value of conventions could be questioned, the traditional public (social) order, framed by the architect's design, was still perceived as indispensable for human freedom and cultural coherence.

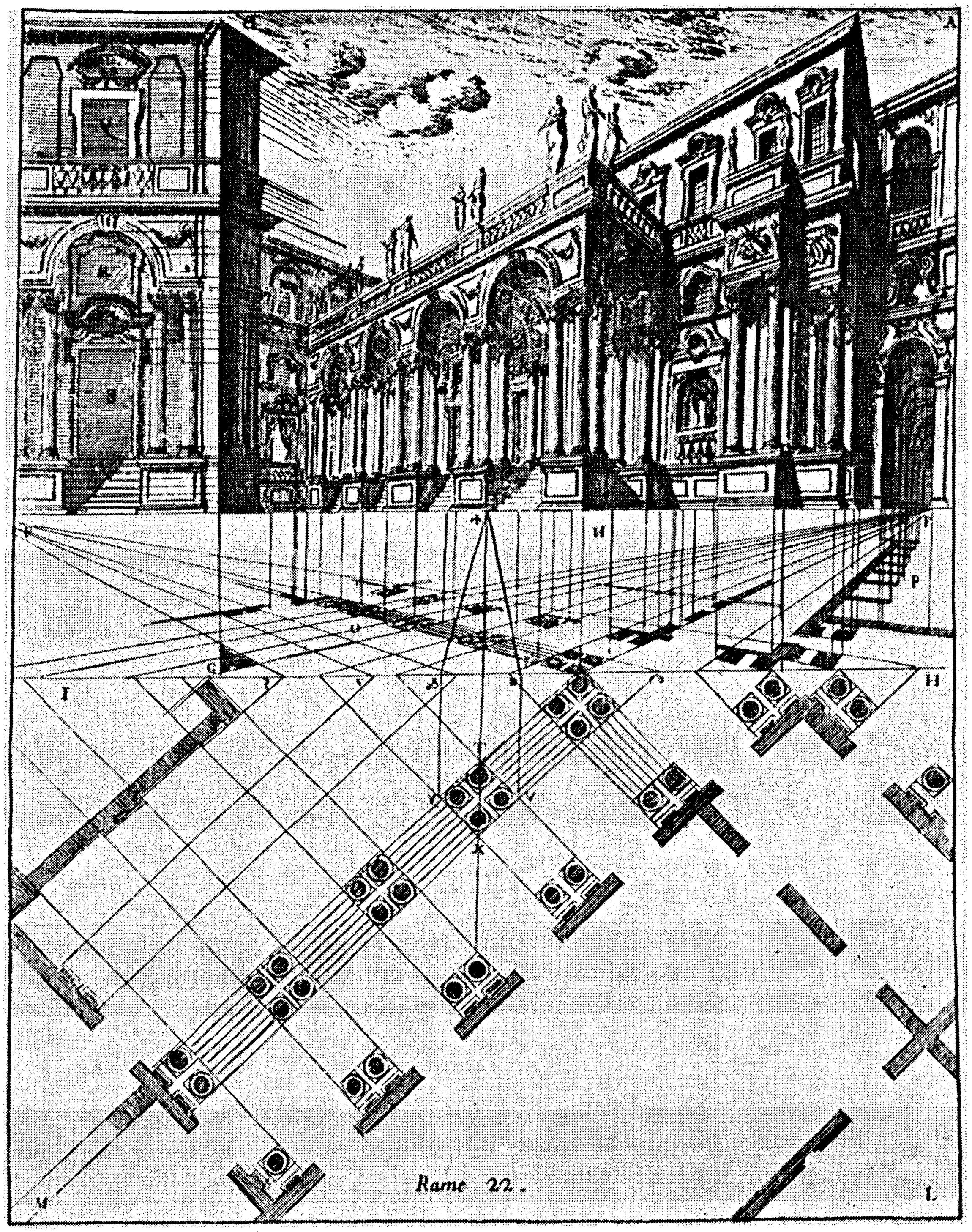
As the seventeenth century drew to a close, geometry increasingly lost its claims to transcendence in science and philosophy. In his *Studies in a Geometry of Situation* (1679), Leibniz proposed a science of extension that, unlike Cartesian analytic geometry, would be integral and not reducible to algebraic equations. But this project of a "descriptive geometry" more universal than algebra could still magically describe the infinite qualitative variety of natural things. This transcendental geometry was part of Leibniz's lifelong dream to postulate a universal science, called by him at various times *lingua universalis, scientia universalis, calculus philosophicus*, and *calculus universalis*. From all the disciplines of human knowledge, he tried to extrapolate the most simple constitutive elements in order to establish the rules of relation by which to organize the whole epistemological field into a "calculus of concepts."[52] The elemental *characteristicae generales* were to be necessarily transcendental, referring to the specificity of things in the world of everyday life. Hence, his "monad," the differential of his calculus, was not a quantitative atom, but necessarily possessed qualities.

Leibniz draws upon Euclidean geometry to explain his *characteristicae*. For example, a circle on a piece of paper is not a true circle, but one of the "universal characters," a vehicle for geometrical truths. It would simply be impossible to reason if these characters did not exist. Leibniz believed that there was not only a similarity between characters and the things they represented,



Anamorphosis as a scientific curiosity, from F. Galli-Bibiena's *Architettura Civile*.

An example of F. Galli-Bibiena's *scena per angolo,* from his own *Architettura Civile.*



but that the order of characters corresponded to the order of things.[53] Hence discovering the appropriate characters in every field of knowledge makes it possible to achieve a complete systematization of the universe, thus forging "a new crucial instrument for the practical objectives of humanity."[54]

Leibniz's science of combinations was the last great metaphysical system; it was, in fact, the culmination of a long tradition of conceptual structures founded on the belief that it was possible to reflect the absolute order of the cosmos. It was a set of rules formulated with the intention of rendering all possible combinations among the primary elements of things, thus making possible the "calculation" of their origins and destinies—an intention similar to that of medieval cabalists and seventeenth-century Pansophists. Leibniz's dream of an encyclopedia related to a universal language, however, was also not unlike the systematization of knowledge postulated by d'Alembert; although it retained a classical ontology, the work of Leibniz represented the moment of transformation of philosophy into a general epistemology—an epistemology not grounded in the traditional notions of theology or metaphysics. His vision of the consequences of systematization was, indeed, a prophecy of technology.

Early in the eighteenth century, Fontenelle, the famous historian of the Royal Academy of Science, denied the transcendental dimension of Leibniz's calculus. In his *Eléments de la Géometrié de l'Infini* (1727), he asserted that geometry was purely intellectual, and independent of the immediate description and existence of the figures whose properties it discovered.[55] He emphasized that infinity, whose existence it was possible to demonstrate in geometry, was only a number, much like the finite spaces that it determined. This infinity had nothing to do with the limitless extension that was usually imagined in association with the word; "metaphysical infinity" could not be applied to numbers or extension, where it has always caused confusion.

Fontenelle was responsible for the establishment of the program to systematize knowledge at the Royal Academy of Science.[56] Aware of the limitations of the traditional seventeenth-century ontological systems that "knew it all in advance," he believed that knowledge should derive from quantitative observation and experimentation. Without ever accepting Newton's philosophy, Fontenelle endorsed the existence of a general geometrical space in which all phenomena were contained. If all nature "consisted of innumerable combinations among figures and motions," then geometry, being the only science capable of determining figures and calculating motions, was absolutely indispensable in physics.[57] Only geometry appeared evident in astronomy, optics, and mechanics. Other phenomena, such as the illness of animals or the fermentation of liquids, although they could not be conceived with the same clarity "due to the great complexity of their motions and figures," were also, in Fontenelle's opinion, dominated by geometry. Thus was postulated the mathematical imperialism of modern science. Fontenelle's general geometry, at the level of technical action and mechanics, was without symbolic implication.

It could be said that after Leibniz, the human intellect lost its immanent power of transcendence. Correlatively, geometry and number became mere formal entities, instruments of technique. The Baroque synthesis was subverted at its very roots. And although Euclidean geometry maintained during the Enlightenment a residual symbolic dimension, the freedom and autonomy of geometrical applications in technical disciplines was firmly and irrevocably established. This transformation propitiated the development of statics and strength of materials, as well as the great interest in technical problems that would characterize eighteenth-century architecture.

Education: Civil Architecture and Engineering

The Royal Academy of Architecture was founded in 1671 to elucidate the beauty of buildings and to provide a means for the instruction of young architects.[58] The best architects in France would convene once a week to discuss their ideas, and the rules emerging from these discussions would be taught in public courses two days a week.[59] The academy's first formally appointed professor was François Blondel, who stressed the importance of mathematical disciplines, geometry, perspective, stonecutting, and mechanics, all within a Baroque framework. But in 1687 he was replaced by P. de la Hire, a well-known geometrician and architect, a member also of the Academy of Sciences and a disciple of Desargues. Thereafter, the weekly deliberations were mostly addressed to problems of statics, stereotomy, surveying, and mensuration.[60]

De la Hire introduced in the academy questions concerning the equilibrium of arches and provided solutions based on Galilean mechanics.[61] He broached the possibility of applying practical geometry to the technical problems of architecture apart from symbolic or aesthetic considerations.[62] In 1711 the academy devoted many sessions to examine de la Hire's theory about the thrust of vaults, and it was generally agreed that his rules were founded on sound geometrical principles. But because these rules were based on a hypothesis of infinitely polished voussoirs, the architects realized it could not be applied in practice.[63] The distance between the theory of statics and the actual behavior of materials would be a problem throughout the eighteenth century. Still, the early detection of this issue is significant, for it implied a general perception of a very different nature than what was presented in the Baroque synthesis. Geometry could now be regarded as a simple tool capable of determining the dimensions of structural components in relation to the laws of mechanics (with all the problems of true effectiveness that this involved).

André Felibien, Pierre Bullet, and Antoine Desgodetz also presented a great number of papers on technical problems to the academy during the early eighteenth century. Between 1719 and 1728, the period in which Desgodetz was the holder of the professorship, the weekly sessions were devoted almost exclusively to the discussion of legal problems and to the establishment of precise methods of mensuration.[64] In 1730 abbé Camus, also a member of the Royal Academy of Sciences, began to teach mathematics to the architects at their academy.

After 1750 the architects' interest in mathematics and geometrical methods generally flagged, while their concerns with the more specifically technical problems heightened. The discussions now centered on, among other things, recently invented machines, techniques for producing better glass, methods for centering, and the quality of building materials. Perronet, Régemorte, and Soufflot presented papers based on the results of quantitative experiments pertaining to the strength of materials. In his work on the origins of architecture, read at the academy in 1745, G. D'Isle—while crediting Vitruvius's mythical account—argued that geometry's role was purely practical. He thought it sharpened the intellect and was useful for surveying, leveling, mensuration, and the drawing of plans and maps.[65]

In a letter addressed to J. A. Gabriel, read at the academy in February 1776, D'Angiviller, *directeur general des bâtimens*, expressed his dissatisfaction with the lack of positive results produced by the institution. He reminded architects that the academy had been established "to maintain and perfect" their art. He emphasized that teaching and criticism were not enough. Discussions on taste, physics, and the exact sciences provided, in his opinion, more than enough material for research. And yet architects seemed to be uncommitted, and their work was not at the level of "other academic institutions that every year enrich Europe with their discoveries."[66] The identification of architecture with the ideals of science could hardly be more explicit. The rationalization of traditional practice and the establishment of truly effective rules and precepts were always important concerns of the academic program, but they would only become exclusive interests in nineteenth-century academicism.

Indeed, it should be remembered that the Royal Academy of Architecture, until its functions were suspended in 1793, always managed to reconcile reason and progress with tradition and a belief in the necessity of absolute rules. Discussions centered around good taste, the meaning of the great Renaissance treatises, and the significance of ancient buildings—all of which indicated a general belief in the transcendent character of *mathemata*. This belief accounts for the profound differences, often disregarded by historians, between the eighteenth-century academy and the *École des Beaux Arts* after the French Revolution. Having accepted art as a synonym of formal manipulation, contemporary architects have often misinterpreted the meaning of the apparent reaction of the *Beaux Arts* against technology and its pedagogical programs. It is important to emphasize that academicism, that is, the reduction of practice to a rational theory, together with the application of positive reason to planning (composition) and style (decoration), became dominant only in nineteenth-century architectural education, after Durand's theory was published and taught at the *École Polytechnique* (see chapter 9). During the eighteenth century, the academy provided lectures on mathematical subjects, but the architect was still fundamentally apprenticed as a builder. The objective was to teach young architects how their work could embody taste, that is, a meaningful order, rather than how to implement rules of formal logic.

The Royal Academy of Architecture was the only institution in Europe offering instruction in architecture until Jacques-François Blondel started to teach his own independent course in 1742. He thought of it as similar to other public lectures on physics, geometry, and perspective, which had been offered by Camus, Le Clerc, and Nollet.[67] Thus architecture became an important part of the Enlightenment's program of knowledge.

Blondel offered an elementary course on good taste and two electives: one for architects, concentrating on theory and proportions; and one for builders that was totally devoted to practical geometry and the mechanical arts. Blondel believed that architects should not only know perspective, mensuration, human proportions, surveying, the properties of the conic sections for stonecutting or how to elaborate precise cost estimates; they should be able to apply all these sciences to practice.[68] Indeed, after emphasizing in his *Cours* the knowledge common to architects and engineers, Blondel complained because the former, although usually knowledgeable in theory, "ignored the laws of proportion in their facades" as well as the rules of geometry and trigonometry in surveying. His dream of seeing students apply theory directly, without first having to undergo traditional practice and apprenticeship, constituted a fundamental *raison d'être* for the foundation of his school and is still the basis of most modern architectural institutions.

Only after midcentury did the fields of professional action of architects and civil and military engineers become more clearly defined. Specialization in bridge construction was, indeed, a relatively late phenomenon. Not until 1688 was official certification required for this type of work. And until the end of the seventeenth century, the title of *ingenieur du Roi* was granted indiscriminately to engineers, masons, and architects.[69] Although the *Corps de Ponts et Chaussées* was founded in 1715, the need to unify surveying and design-presentation methods and to improve the training of young engineers did not become truly evident until 1745. Finally, in 1747, Jean-Rodolphe Perronet was called to Paris and appointed head of a new official institution: the *Bureau des Dessinateurs.*

Perronet divided his office into three "classes"; each class was based on the individual's knowledge of practical geometry and its applications to design, stereotomy, mechanics, hydraulics, cost estimates, surveying, and mensuration. In 1756 the *École des Ponts et Chaussées* replaced the previous institution and almost immediately acquired enormous prestige in France and the rest of Europe. In his biography of Perronet, Riche de Prony emphasized the importance of this first school of civil engineering. Perronet had instituted a system of mutual teaching, so that the most advanced students became tutors of their less knowledgeable colleagues. Previously, the members of the *Corps de Ponts et Chaussées* did not have a full curriculum and a sound theoretical background. Riche de Prony thought this problem had been finally solved after Perronet founded his school.[70]

The curriculum of the institution did not remain constant, but normally it included algebra, analytic and Euclidean geometries, the properties of the conic sections, mechanics, hydraulics, and stereotomy. Infinitesimal calculus was sometimes taught, but was never mandatory. Physics, construction methods, mensuration, and natural history had to be taken elsewhere. The engineers were also required to learn artistic drawing and graphic design, courses usually taught by such architects as Blondel. After the French Revolution, the *École des Ponts et Chaussées* was transformed into a school of specialization for students who had already finished their preparation at the *École Polytechnique*.

Education: Military Architecture

The "universal men" of the Renaissance were the first to concern themselves with military architecture, that is, the geometrical determination of the elements of fortification. They considered this science to be a liberal art. During the seventeenth century, military engineers were recruited at random among old officers, builders, and architects. In spite of the great number of treatises on fortification that were published throughout Europe during this century, engineers always learned their craft from their predecessors. Until Sebastien Le Prestre de Vauban instituted a compulsory entrance examination in 1697, the French *Corps du Génie* did not have a defined structure.[71]

The first official examiners were J. Sauveur and F. Chevallier, two geometricians of the Royal Academy of Science. The *marquis* D'Asfeld, *directeur général des fortifications* (1715–1743), wrote to Chevallier stipulating the type of knowledge that should be required to pass the examination. The new officers had to be capable in drawing and mensuration of fortifications, estimating costs, and setting up construction schedules. They had to be familiar with arithmetic, geometry, leveling, and some basic aspects of mechanics and hydraulics, and they had to know how to draw maps. He recommended three theoretical works: Frezier's treatise on stereotomy and Forest de Bélidor's *Science des Ingenieurs* and *Architecture Hydraulique*.[72]

In 1720 the king founded five schools to prepare officers for the *Corps d'Artillerie*; the curricula were based on common mathematical disciplines.[73] But only in 1744 did a royal *arrêt* provide the *Corps du Génie* with a general organization and statutes.[74] In 1748 the *École Royale du Génie* was founded at Meziéres, with the abbé Camus as official examiner. In 1755 his functions were extended to cover the artillery schools, and for three years both *corps* worked together. Their textbook was Camus's *Cours de Mathématiques*. This work, published between 1749 and 1752, discussed arithmetic, geometry, the use of proportions, and the basic tenets of statics and mechanics. It was a rather elementary book based on Camus's lessons to the architects of the academy.

As early as 1753, C. Bossut, a member of the Academy of Sciences and "free associate" of the Academy of Architecture, who had been appointed professor of mathematics at Mezières, tried to introduce perspective, calculus, and dynamics into the curriculum, but the customary examination of Camus was not immediately modified. During the second half of the century, more emphasis was given to experimental physics and practical applications. The abbé Nollet taught physics at Mezières, and a new director, Ramsault, sought permission from the minister to substitute Bossut's course for Camus's. Ramsault felt that in order to improve the quality of the school, the engineers should learn algebra, analytic geometry, and calculus. Only then would they be capable of solving problems of mechanics, strength of materials, retaining walls, and hydraulics. But he also believed that these sciences were too complicated for the majority of students. Therefore he recommended that these subjects be taught in private only to the qualified few.[75] This undoubtedly epitomizes the age's ambivalent attitude toward the possibility of solving technical problems through an *effective* implementation of theory.

Bossut wrote numerous treatises from a truly protopositivistic vantage point, insisting on the uselessness of compiling empirical data without a theory or hypothesis to relate them.[76] His works, which appeared after 1772, were conceived as part of a grand scheme for a mathematical curriculum that was to include, apart from the traditional subjects, analytic geometry, algebra, hydrodynamics, and calculus. His *Traité Elémentaire de Géométrie et de la Manière d'Appliquer l'Algebre à la Géométrie* (1777), regards algebra as "purely intellectual," using signs to represent general relations, while geometry is considered "less abstract" and capable of treating extension only in the figurative sense. Geometry, then, "necessarily [implies] the participation of sight and touch" in establishing relations among lines, surfaces, and bodies. The text also contained such curious problems as the tracing of arches using analytic geometry so that their configurations could follow the determinate equation of a conic section.

Bossut's attempts to clarify the relations between geometry and algebra and to find practical applications of analytic geometry in building constitute two important contributions to the process of functionalization of geometry. His work surely stimulated his young assistant Gaspard Monge, whose descriptive geometry would eventually have enormous repercussions for architecture. When Bossut was finally appointed official examiner of the school in 1770, Monge took over as professor of mathematics. After 1772 a new curriculum gave greater importance to the teaching of geometrical projections and perspective. Both subjects were now considered tools of precision, indispensable to the military engineer. Geometrical drawing was studied "to find the configuration of any piece of stone or wood" in an architectural element and to trace the five orders, as well as the plans, sections, and elevations of civil and military buildings. Perspective was taught not only "to determine geometrically the shadows of drawing or watercolor" but because it was believed essential for a *true* perception of reality. The study of the rules of perspective "is necessary to educate the eye for the drawing of detailed maps in military operations."[77]

This last curriculum, which thereafter did not change much, also included Nollet's course on experimental physics, natural science, and visits to various industries. The vitality of the school now began to decline, and finally, in 1794 it closed down.[78] Like the *École des Ponts et Chaussées,* this institution was an immediate predecessor of the *École Polytechnique.* The effort to link scientific theory with technical knowledge had a long history, and after 1770, at Mezières, this ideal came close to its realization. Most members of the original academic staff of the world's first truly technological school had received their education in the *École du Génie.*

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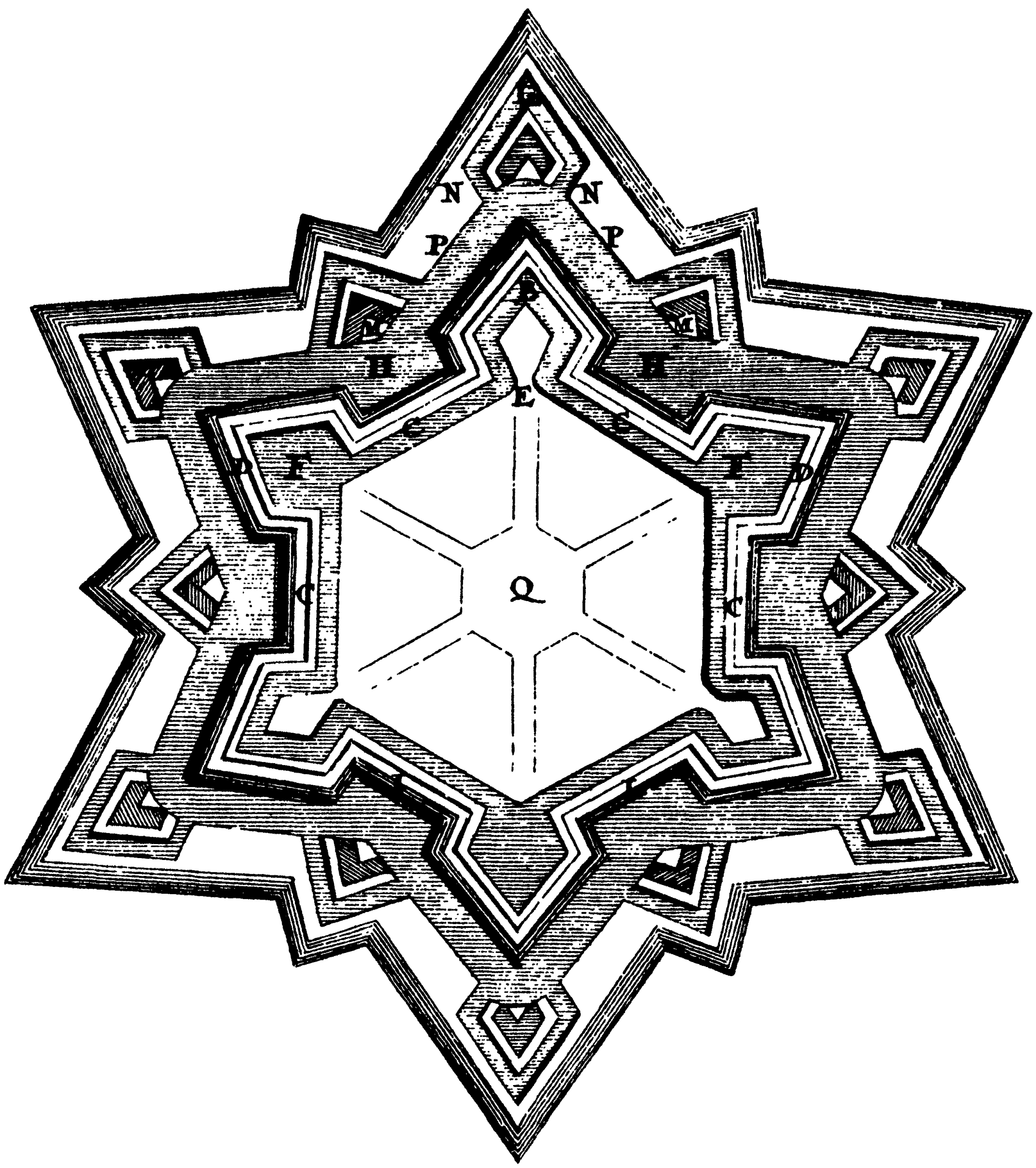
FORTIFICATION, MENSURATION, AND STEREOTOMY

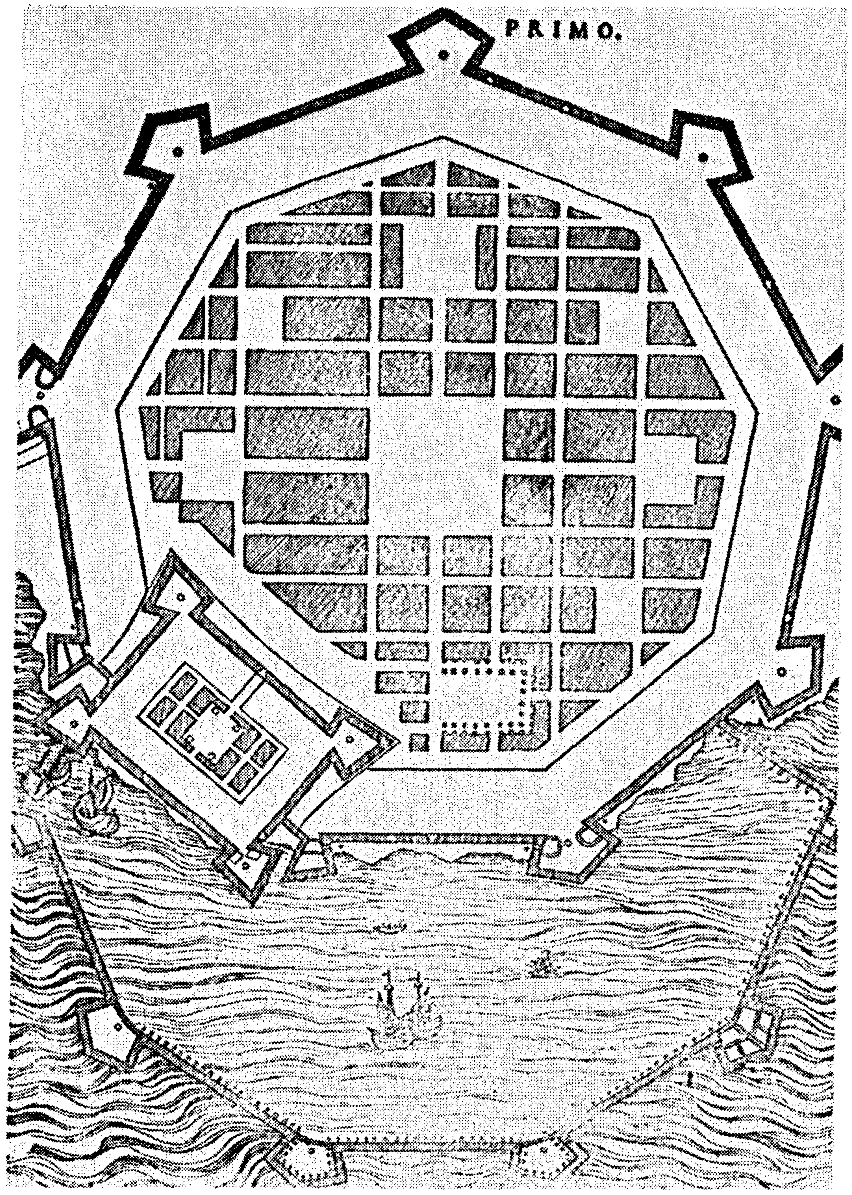


Treatises on fortification published during the second half of the sixteenth century utilized rules of practical geometry to determine the configurations of polygonal plans and their elements. Girolamo Cataneo's *Dell'Arte Militare* (1559) falls within this category. His work, however, was not systematic. Unconcerned with the implications of the geometrical order, he merely described a still meaningful craft.[1] In Simon Stevin's *Oeuvres Mathématiques*, first published in Flemish in 1584, fortification was discussed alongside perspective, statics, and mensuration. This was perhaps the first universal mathematical encyclopedia, a forerunner of the many popular works of this type published in the seventeenth century. The section on fortification was similar to Cataneo's, teaching the tracing of polygonal plans through geometrical operations.[2]

A great number of treatises on military architecture were published in Europe during the seventeenth century. Practically all of them included a description of the geometrical operations necessary to trace the polygonal plans of fortifications. S. Marolois's book on practical geometry, *Géometrie . . . Necessaire à la Fortification* (1628), explained the use of the compass in surveying and many other operations.[3] Also described were methods of calculating the volumes of material necessary to build different parts of a fortification. In another book, *Fortification ou Architecture Militaire* (1628), Marolois used trigonometry to calculate the angles and dimensions of these parts.[4] Although fascinated by the precision of geometrical operations, he disregarded the problems and limitations of reality. Significantly, irregular fortifications, whose perimeters were not an ideal polygon, were hardly mentioned. Another treatise with the same interests was N. Goldman's *La Nouvelle Fortification* (1645). Goldman identified the art of fortification with geometry, claiming that the careful use of geometrical operations was imperative for this "liberal art" to fulfill its purposes.[5]

Milliet Dechales's *L'Art de Fortifier* (1677) betrayed an even greater interest in geometrical operations and regular polygons. All military problems were described in terms of lines and angles, and the text itself was written *more geometrico*.[6] But in the context of Dechales's *Cursus seu Mundus Mathematicus* (1674), the geometrical encyclopedia of knowledge that Guarini so admired as an example of absolute certainty, the symbolic intentionality inherent in these geometrical operations becomes immediately evident.

The underlying intentions of seventeenth-century treatises on fortification are perhaps best discerned in Bernard Palissy's *Recepte*



Plan of a nine-sided polygonal fortification, an example from the Renaissance treatise of P. Cataneo, *Architettura* (1554).

Véritable. After confessing his ignorance of rhetoric, Greek, and Hebrew, this "humble craftsman" defended his design of a fortification against critics who accused him of lacking military experience. He thought that "military art" derived more from a natural sense than practice. Having received from God his ability to understand the art of the land, he could certainly design a fortified city, "consisting mainly of tracings and lines of geometry."[7]

Palissy believed that existing fortified towns failed because their protecting walls were not really part of the towns' architecture. He tried to find better ideas in the treatises of the old masters, but was sadly disappointed. In desperation, he turned to nature and after traversing woods, mountains, and valleys, he arrived at the sea. It was there that he observed "the miraculous protection of mollusks like oysters and snails."[8] God had given these weak animals the ability to build themselves homes, designed "with so much geometry and architecture that not even King Solomon, with all his wisdom, could have produced something similar."[9] Confronted with this marvelous discovery, he fell on his face and adored God, "Who had created all these things for the service and commodity of man."[10]

The sea snail was clearly the best prototype for a fortified city. In case of siege, the city's inhabitants would only have to give up one compartment at a time, making the city practically impregnable. The sections in a spiral plan would be not only beautiful but also useful as buttresses of the external wall, while in peacetime, the walls could be used for housing. Palissy was convinced that only places that God himself had fortified in nature could be better than this model. He praised the "Sovereign Architect" for his inspiration, which should, he believed, guide the "art of geometry and architecture."

This geometry, which God had given to nature, was reproduced by Palissy and others in their own technical endeavours in order to assure the meaning of their works. Jacques Perret de Chambéry's folio of plates (1594) illustrated polygonal and star-shaped fortifications that were surrounded by inscriptions taken from the Psalms of the New Testament.[11] Perret even thanked God for having allowed him to conceive so many marvelous war machines. And war itself, signifying man's obsession to dominate, was perceived in a transcendent light, as a ritual whose goal was to establish order. Military architecture could thus represent an order in which "all nations may praise the Lord" and "live according to His Holy Laws."

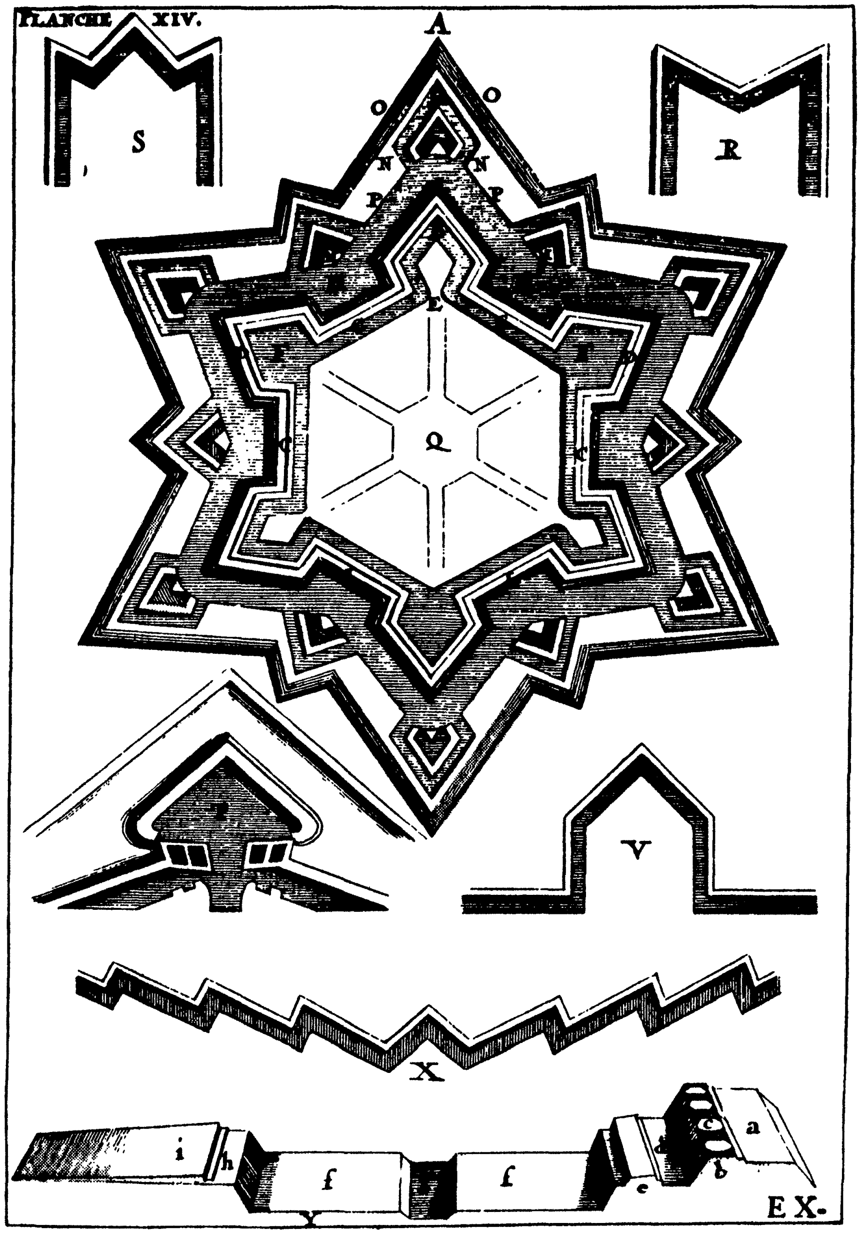
In some early-seventeenth-century treatises, the magical and naturalistic aspects of geometry often appeared to be mere restatements of older Renaissance notions. Such is the case in P. A. Barca's *Avertimenti e Regole* (1620), which recommended the use of square, pentagonal, or hexagonal fortifications since these figures were symbols of the relation between the human body and the cosmos. God, the divine architect, had created the heavens and earth "with weight, number and measurement," conforming everything to the circle, the most perfect figure. Man, on the other hand, "is a small world. . . . His flesh is the earth, his bones are mountains, his veins are rivers, and his stomach is the sea."[12] Similarly, P. Sardi's *Couronne Imperiale de l'Architecture Militaire* (1623) described regular fortifications using the human body as a metaphor. It also stressed the importance of images in teaching the operations of practical geometry.[13]

Gabrielo Busca's *Architettura Militare* (1619) showed less concern for practical geometry. Busca was more interested in the history of military buildings, the significance of their geographical locations, and the relations between rulers and citizens. He was especially concerned with the rituals of foundation deriving from ancient tradition considered necessary for the effectiveness of fortification. These ceremonies involved the tracing of orthogonal paths that divided the city into four parts (the Roman *quadrattura*), which corresponded to the four regions of the sky, thus emulating the cosmic order.[14] Similar concerns can be detected in *L'Architecture Militaire Moderne* (1648) by Mathias Dögen.[15] Although Dögen was more typical in his belief concerning the crucial role of geometrical operations in fortification, he gave equal importance to the description of the heroic deeds that took place in these buildings. He included long sections in which he provided detailed instructions on how to conquer cities, taken from the "laws" established in the Holy Scriptures.

A few exceptional early treatises showed a more pragmatic understanding of military engineering. Jean-Errard de Bar-le-Duc's *Fortification* (1594)[16] advocates that individuals responsible for the fortification or defense of a city should not only be experienced soldiers with military authority but also good geometricians. This would enable them to invent useful machines and to understand how the proper use of proportion can save unnecessary expenses. Consequently, a military engineer also had to be knowledgeable in some aspects of architecture and masonry.[17] Errard believed that the art of fortification consisted in determining the slope and angles of the foundations of walls. But although he included geometrical methods for describing regular polygons, he devoted most of his work to the explanation of irregular fortifications. This was the logical extension of Errard's belief that location and practical considerations had to be taken into account before designing a fortified city. Simply imposing an arbitrary geometrical figure upon a terrain was insufficient; it was imperative to consider its topography and other particularities. Also, Bonaiuto Lorini's *Delle Fortificazioni* (1597) distinguished between the points and lines of the mathematician and the true problems encountered by the "practical mechanic," whose ability consists in knowing how to foresee the difficulties characteristic of the diverse materials with which he must work.[18]

Whatever the limitations of these early discussions on the importance of an effective technical knowledge, which were often motivated (as it became clear in relation to Palissy's work) by an implicit recognition of the transcendent dimension of human action, they do contrast with the seventeenth century's obsession with regular polygons and geometrical methods. Count Pagan, for example, could recognize in 1645 that the "science of fortifications" was not "purely geometrical."[19] Because the objective was "material" and drew its inspiration from experience, "its most essential postulates depend only upon conjecture." Yet Pagan did nothing more than to provide simple recipes for tracing "small, medium, or large" polygonal fortifications, and he included in his treatise only a brief section on irregular fortification. His typically Baroque identification of geometry with reality appeared in two other books, published in 1647 and 1649. In his *Théorie des Planètes*, Pagan adopted the Copernican planetary system. The second work, however, was devoted to astrology; its intent was "to found this science on geometrical and natural principles"—the same principles that lay at the heart of astronomy. The reader may remember how the synthesis between technical and symbolic intentions that motivated the use of geometrical operations during the Baroque period was most prominent in the work of G. Guarini. His *Trattato di Fortificatione* (1676) appears to have been the last book on military architecture that explicitly assigns geometry symbolic or magical significance.

Inevitably, the epistemological revolution influenced the reduction of military architecture into *ars fabricandi*, which is to say in this case, the rules of practical geometry. During the second half of the century, authors like François Blondel and A. Tacquett wrote about "methods" of fortification and discussed their dif-



Hexagonal fortification, plan and details from Felibien's *Principes* (1699).

ferences.[20] And Ozanam's *Traité de Fortification* (1694) took a significant step beyond the Baroque world. Although Ozanam did not discuss ballistics or statics, and while he still believed that regular fortification epitomized the totality of military science, his exposition of the subject was thoroughly systematic. Every problem was solved through a geometrical operation, and nothing was left to chance or personal experience. He included a careful comparative analysis of all existing methods of fortification, including those of Errard, Pagan, Bombelle, Blondel, Sardi, and even Vauban. In his *Cours de Mathématiques . . . Necessaires à un Homme de Guerre* (1699), Ozanam affirmed the priority of mathematics over other sciences, praising its potential to provide absolute certainty. In this and in his works on perspective and anamorphosis, this contemporary of Perrault already perceived mathematics as a merely formal science. He emphasized that, unlike poetry, it did not "provide delicate pleasures" to our "spiritual voluptuousness," its objective being "to prepare men for more solid things."[21]

However, it was the brilliant French Marshall Sebastien Le Prestre de Vauban who first understood the consequences of the Galilean revolution and effectively applied the new science to transform military architecture. Vauban was born in 1633 and was an important figure in the consolidation of France under Louis XIV.[22] He was appointed *commissaire général des fortifications* by Colbert, taking over from a man who apparently had known very little about fortification and who had recommended Renaissance methods, for example, building bastions perpendicular to the walls.[23]

Vauban was responsible for numerous inventions and technical innovations. Generally, however, he retained all the elements of sixteenth-century fortification, developing only Pagan's notion of "defense in depth," which gave greater importance to the "external works"—those parts outside the main wall. Vauban's real contribution took the form of a fundamentally different attitude to the problem. He believed the art of fortification *did not* consist in the application of rules or conceptual geometrical systems, but that it had to derive from experience and common sense.[24] Empirical reality and practical adaptability had to balance geometrical rules.

Significantly, Vauban rejected the idea of writing a book on fortifications.[25] He was convinced that dogmatic systems were totally useless when applied to different situations. For Vauban

Sebastien Le Prestre de Vauban, engraving by Dupuis.

the geographical and topographical particularities of a place were of paramount importance. Only late in his life did he write a formal treatise on attack, defense, and entrenched camps, in which he summarized his experience and conclusions. He also emphasized that to understand his work, no knowledge of geometry was necessary;[26] reality was more important in war than any conceptual knowledge. In order to besiege a city it was not enough to have its plans. These, he said, could be bought in any bookstore. What truly mattered was a first-hand knowledge of the terrain and the city.

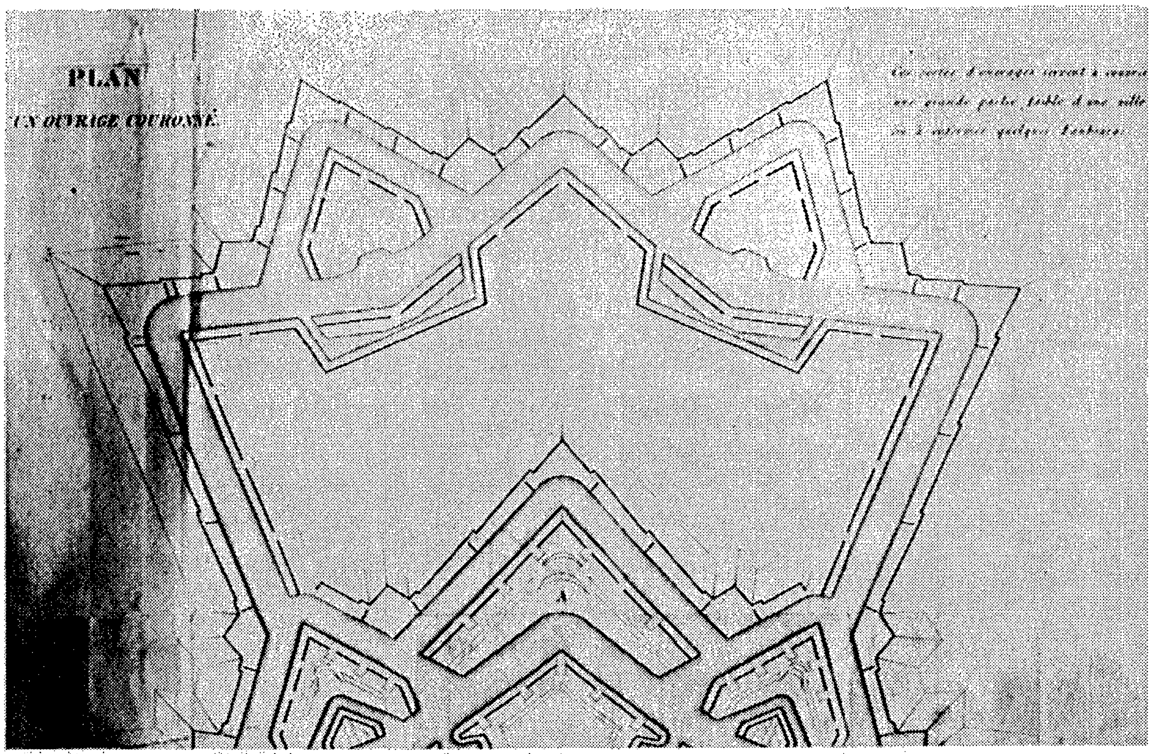
These apparently straightforward remarks are very significant in light of the epistemological revolution and Vauban's special interest in mathematics. His use of the mathematical sciences was clearly devoid of symbolic intent. Vauban constantly employed arithmetic as a tool for cost estimates and statistics; his treatise is full of tables for determining, for example, the amounts of gunpowder, food, infantry, and cavalry that should be available in relation to the number of bastions in a fortification.

Vauban wrote extensively on diverse subjects, but one concern was preeminent: quantitative rational planning.[27] In a paper calling for the reestablishment of the Edict of Nântes, he utilized statistics to argue for the end of the deportation of Protestants, thereby avoiding moral discussions and reducing the problem to a question of political economy.[28] In his study of Vezelay's census, he used ethnic and demographic statistics to devise a method establishing a more equitable taxation law. In 1699 he wrote a report on the French colonies in America, concentrating on the potential of Canada, and described the way to settle new towns through carefully planned stages.[29] There was no trace here of the myths and rituals of foundation evident earlier in the century. For Vauban, only rational quantitative considerations were to determine the choice of a site for a new city. No thought was spent on the traditional question of the place's "meaning."

The precision, order, and clarity of Vauban's own projects, including his specifications and cost estimates, were novel and remarkable. The reports he prepared for each one of his fortifications always contained four parts: (1) general precedents of the work; (2) a detailed description of the constituent parts with reference to the drawings; (3) cost estimates after a careful calculation of volumes of materials used; and (4) special features or advantages of the work. His concern for economy and efficiency in building could also be seen in an earlier work that listed 143 observations on such subjects as foundations, masonry, plan distributions, carpentry, and construction of doors and windows.[30] In a paper on the functions of officers in charge of fortification, he attributed the high cost of these works to the lack of organization in their construction.[31] His method for the presentation of projects and reports was in itself an attempt to overcome these problems through rationalization of the whole building process.

In the same paper, Vauban also provided a profile of a good military engineer. Young men willing to enter the *corps* should have some knowledge of mathematics, geometry, trigonometry, surveying, geography, civil architecture, and drawing. He believed that an examination to test candidates' abilities was necessary and that it alone should be considered in granting appointments. After 1699 such an examination became institutionalized. That same year Vauban was voted an honorary member of the Royal Academy of Science. After his death in 1707, Fontenelle eulogized the late *marechal de France*,[32] pointing out that he had brought mathematics from heaven to solve the needs of man. This statement alone, equating Vauban's achievements to Galileo's, would be sufficient to postulate the *marechal* as the first modern engineer. Fontenelle also emphasized the importance of Vauban's rejection of the older systems of fortification. Vauban had proved through his practice that there was no universal manner applicable to all situations. The difficult problems of military art could not be solved by fixed rules, but required the natural resources of genius.

Vauban was also the first to apply a different sort of fixed rules—those of mechanics—to determine the necessary thickness of fortification walls. His contribution represented the first true application of statics to military engineering.[33] Vauban also successfully modified the shape and disposition of bastions in relation to the lines and properties of artillery fire. This was an old concern expressed by the architects of the Renaissance. Vauban's seemingly minimal adjustments were so effective, however, that they were copied throughout Europe during the eighteenth and nineteenth centuries. With Vauban, geometry in fortification became a truly efficient instrument for determining the configuration of elements in relation to the location of artillery, topography, and the physical characteristics of cities. His work and methods were totally different from those of his predecessors and contemporaries, for whom the regular geometrical shape of fortifications was an end in itself, full of symbolic connotations, constituting both the most important part of the process and its ultimate justification.



Detail for the external works of a fortification, from Vauban's *Défense des Places*.

By the end of the seventeenth century, Vauban was already famous in Europe. Even before his death, various authors tried to work his contributions into a "system," which only revealed how difficult it was for his contemporaries to understand his thought and the transformations it implied. Such was the case in treatises published between 1669 and 1713 by Cambray, Pfeffinger, Sturm, and even Christian Wolff, who reproduced Vauban's "system" in his *Cours de Mathématiques*.[34] In the eighteenth century, various publications still compared Vauban's system to some others, and as late as 1861 Prevost de Vernoist defended Vauban's method as the best.[35] All this notwithstanding, the number of treatises on fortification published during the Enlightenment decreased conspicuously. Especially after the second decade of the eighteenth century, fortification was no longer the dominant theme of military engineering.

The engineers of the eighteenth century, educated in the new technical schools, came to realize that the determination of the polygonal plan of a fortification was only a minor problem compared to the questions of mechanics or hydraulics, which had to be resolved in order to build adequately and efficiently. This new scientific interest was manifested initially in the works of Bernard Forest de Bélidor, professor of mathematics in the artillery schools and author of three influential texts. Bélidor was a member of the scientific societies of London and Prussia and a *membre correspondant* of the Parisian Academy of Science.

In his most important book, *La Science des Ingénieurs* (1729), he coherently outlined the discoveries and contributions of Vauban. Bélidor, better than most, could appreciate Vauban's achievement. As the author of the first truly scientific work on military architecture,[36] he criticized sixteenth- and seventeenth-century treatises for having merely taught how to trace polygons and the names of parts without having dealt with the real problems of construction. Likewise, he rejected Pagan's book and, significantly, all those treatises that pretended to disclose Vauban's "system," works which, he remarked, the *marechal* himself had disowned.

La Science des Ingénieurs went into many editions, including two in the nineteenth century annotated by Navier, the famous professor of structural design at the *École Polytechnique*. The book was divided into six chapters whose contents and objectives explained the "science" of the engineer. The first chapter was dedicated to the determination of dimensions in masonry retaining walls (that is, the external walls of fortifications) in relation to the thrust of the earth and the spacing between buttresses. In the second chapter, Bélidor examined the thrust of vaults and determined general laws by which to find the dimensions of vertical structural elements with regard to vaults' shapes and uses in civil and military buildings. The third chapter analyzed the quality of materials and their appropriate uses, describing the building procedure for the most important parts of a fortification, "from the tracing of the project to its complete execution."[37] The fourth and fifth chapters, significantly, concentrated on civil architecture. They dealt with technical problems, providing some practical rules for buildings, and included a long section on the five classical orders. The final chapter was an example of *devis*: the application of the science to one specific project; this entailed the precise elaboration of specifications and cost estimates in the manner of Vauban's report for Neuf-Brisach.

A conflict between a theory intentionally postulated as *ars fabricandi* and an eminently traditional practice is explicit from the very first pages. Bélidor believed that mathematics was finally capable of perfecting the arts, but that very few people understood its power.[38] Artists and craftsmen retained greater faith in practice to solve technical problems. This prejudice, thought Bélidor, had to be overcome. Reason must elucidate experience; otherwise, knowledge was imperfect: "In *architecture*, for example, no progress can be observed with regard to certain essential points that constitute its basis, in spite of the fact that this art has been cultivated for a very long time."[39] Bélidor declared that with the exception of a few rules about "convenience and taste for decoration," architecture did not have precise and exact principles with respect to "all its other parts" (for example, principles of statics for determining the dimensions of structural elements and avoiding the use of superfluous material).

Bélidor stressed that architecture, having always depended on proportions, should by definition be subject to mathematics. Architects of the past, "lacking any knowledge of mechanics or algebra," had always created excessively expensive works; they had been incapable of saving material since they were unsure about the stability of their buildings. Young architects, admitted Bélidor, learn through experience, but they should not waste their lives repeating what had already been done. He thought it was possible to replace experience by an *ars fabricandi* based on geometry and mathematics: "This knowledge will be as instructive as their own practice."[40]

Bélidor's treatise constitutes the first methodical attempt to solve the problems of construction in engineering and architecture through the application of geometrical rules founded on statics. In his *Nouveau Cours de Mathématique* (1725) for the artillery schools, he refused to deal with useless mathematical knowledge. Instead, he applied the laws of dynamics to "the art of throwing bombs," summarized Varignon's book on mechanics, and rejected the merely geometrical rules of late-Gothic ancestry that had been often used to determine the dimensions of the vertical supporting elements of arches and vaults (rules popularized by Derand and F. Blondel during the seventeenth century).[41]

Some interesting comments, from the perspective of the early nineteenth century, were added by Navier to *La Science*. Navier asserted that the hypothesis in Bélidor's solution to the problem of retaining walls was false, that it was not "in accordance with the phenomenon as it occurs in nature."[42] Bélidor considered the walls as solid pieces, disregarding the true composition of masonry. Nevertheless, Navier justified Bélidor's hypothesis by pointing out that in the early eighteenth century, the solution had to appear as absolutely certain in order to convince skeptical practitioners. In the second chapter, Bélidor applied De la Hire's mechanical hypothesis about the behavior of vaults. Navier added a note in a similar vein, stating that De la Hire's hypothesis had been generally accepted until, after much systematic observation, a new theory was established late in the eighteenth century that actually considered "natural effects." The implications of Navier's different standpoint will become clear in a later chapter. It is important to emphasize here, however, the great significance of Bélidor's treatise, which was considered by Navier as the point of departure for effective scientific engineering, and which in spite of its "mistakes" demonstrated technological interest.

In chapter 4, Bélidor focuses on the problem of distribution and the general characteristics of fortified cities and military buildings. Like most French writers on architecture during the eighteenth century, he considered "convenience" a fundamental value. Consequently, he wished to provide general rules for building derived from common sense, but which also posited a relation between physical proportions in general and convenience. Although engineers could not pretend to be first-rate architects, they should appreciate the proportions necessary for a building to be "comfortable and graceful." After Bélidor's description of building details and construction systems, Navier added a note indicating that anything missing could be found in Rondelet's

Art de Bâtir (1802). The relation established between Bélidor's *Science* and the first truly effective textbook on construction is, once again, highly revealing.[43]

The theme of the sixth chapter would also receive its definitive formulation toward the beginning of the nineteenth century in Rondelet's book. This was the elaboration of *devis*, or the description of comprehensive programs for the planning of building operations that included, at a conceptual level, considerations that had been previously taken into account only through practice. Bélidor stressed that these programs were the most important part of engineering theory since they discussed detailed specifications, the order in which the work must proceed, exact dimensions of even the smallest parts, and "all circumstances of construction" that might help to prevent accidents.[44] These programs were already attempts to *reduce* practice to a preconceived rational plan. Bélidor took the idea from Vauban and perhaps also from Pierre Bullet, an architect of the academy who, also late in the seventeenth century, had shown the importance of *devis* in architecture. But in his *Science*, Bélidor defined precisely the objectives of such programs, asserting their crucial importance for scientific building.

Now we come to what might appear as the odd chapter from the standpoint of nineteenth- and twentieth-century engineering. For Bélidor, an engineer should be as capable of building a palace as a fortification, and chapter 5 betrays his traditional concern with decoration. Significantly, he also criticized in this context Baroque treatises that had ignored the rules of "Vitruvius, Palladio, Vignola or Scamozzi" and taught instead only methods for tracing polygons.[45] Bélidor was also critical of "the confusion of Gothic architecture" and the exaggerations of Baroque artists like Guarini.[46] He obviously rejected all magical and symbolic implications of Baroque geometrical operations, but he believed instead that the rules of the classical orders were extremely important for engineers. So rather than trying to improve upon the "science" of proportions, which "had already attained a high degree of perfection," he chose to reproduce Vignola's rules "for the simplicity of [Vignola's] recommended measurements."[47]

After repeating the Vitruvian myth on the origin of the orders, Bélidor devoted more than seventy pages to their rules. He then set down some maxims on the problem of "distribution"—in his opinion, the most essential part of architecture because it dealt with the efficient use of available land.[48] Bélidor's "wise appreciation" of this problem won the approval of Navier, who pointed

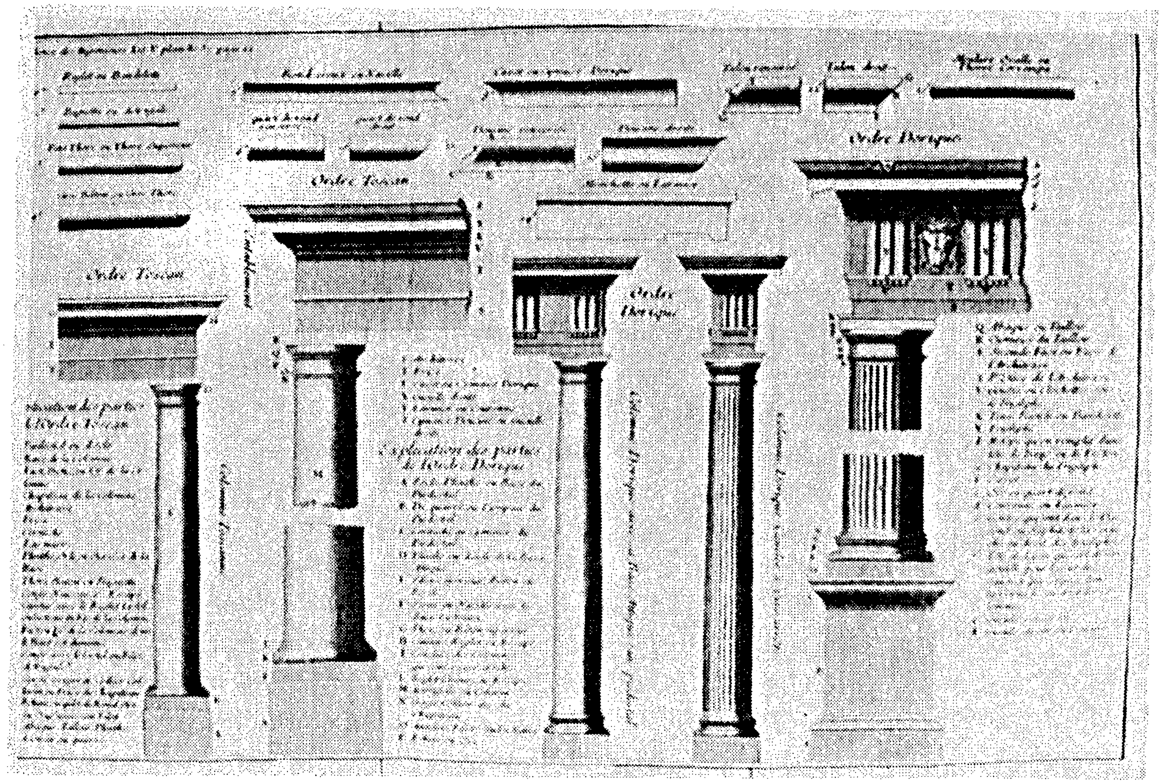


Plate showing the parts of the Tuscan and the Doric orders, from Bélidor's *Science des Ingénieurs.*

out that these maxims had been consecrated and developed by Durand in his *Précis des Leçons* and were "treasured" by the students of the *École Polytechnique*. Navier added, however, that other aspects of this chapter were not as important as Bélidor had imagined. For example, the rules of the classical orders were useful but not fundamental. "The architect," wrote Navier, "should know them like a writer grasps the use of language. With this knowledge, however, one can still produce very bad works."[49]

For Navier, the rules of the orders were already a formal system, which was not necessarily meaningful in itself. In his opinion, only Durand had been capable of truly overcoming old prejudices by placing architecture on solid and positive grounds that recognized convenience as a unique and exclusive principle: "a perfect relation established between the disposition of a building and the use to which it is destined."[50] Navier emphasized that design was nothing more than "the resolution of a problem whose data are found in the conditions of *solidity*, *economy*, and *utility* that the work must fulfill."[51] Durand had shown how this principle of convenience, far from contradicting decoration, was the only sure guide to providing building with true character and beauty.[52]

The similarities and differences that Navier observed between Bélidor and Durand are significant and illuminate the immense distance between them. Bélidor clearly attached great importance to traditional architectural theory and imagined it as part of the science of the engineer, perceiving no contradictions between the two fields. To his way of thinking, the time-honored Vitruvian categories of decoration, distribution, and solidity of construction were not independent values, but arose from more fundamental, unstated and irreducible symbolic intentions.

In this respect, it is interesting to note how Vauban defended his projects to beautify the gateways of his fortifications from official criticism. While Louvois cared only to save the money and effort involved in this task, Vauban insisted upon the importance of entry and its meaning. The presence of this residual symbolism, perhaps not suprising in Bélidor's teacher, appeared even more explicitly after 1750. The engineer Joseph de Fallois published in 1768 a work entitled *L'École de la Fortification*, whose stated objective was to enlarge upon Bélidor's *Science*.[53] It might be expected that this work would develop the scientific principles and technological interests found in Bélidor's book. Instead, De Fallois emphasized the importance of geometrical methods for tracing the plans of polygonal fortifications; he also reproduced Coëhorn and Vauban's "systems" and repeated some of the same rules concerning the resolution of problems in mechanics that had been in use fifty years earlier. Even more revealing was De Fallois's attempt to establish the fundamental and general principles of military building. Following a train of thought very similar to Laugier's, and obsessed like so many of his contemporaries with finding the natural origin of his activity, De Fallois drew up fifteen basic principles that could be derived from the original character of primitive fortification: man's need to defend himself from animals and other men. This mythical history clearly acted as a metaphysical justification for established principles. This was perhaps the last work on military engineering in which a myth constituted the ultimate foundation of practice and such speculation was intended to ensure the transcendence of military building.

Mensuration

At this point, it is important to examine the applications of practical geometry and arithmetic to mensuration, surveying, and other aspects of the building craft. In Bernard Palissy's *Recepte Véritable*, the symbolic content of practical geometry used in the configuration of the physical world is made evident by its inclusion in the traditional anthropocosmological structure. This is brought out in an imaginary midnight dialogue among his instruments.[54] The compass, the ruler, the plummet, the level, the astrolabe, and a fixed and an adjustable triangle discuss their respective attributes, stating the roles they play in construction and the metaphors they embody. The compass, for example, demands a place of honor among the others, being in charge of "conducting the measure of all things. . . . Men without compass are admonished and asked to live according to the compass." The ruler describes its merits in these terms: "I conduct all things directly. . . . Of an individual of dissolute customs, one says he leads an unruly life. . . . Without me he cannot live rightly." And the triangle claims, "I determine the perpendicular angles of corners. . . . No building could stand without my help." The astrolabe then points out that it has the greatest merit because its domain is beyond the clouds and it determines the weather, the seasons, fertility, and sterility. Finally intervening in the noisy dispute, Palissy tells his instruments that the true place of honor belongs to man, who gave them all form.

The use of practical geometry for the tracing of walls and foundations (in order to ensure verticality or symmetry) is obviously as old as the building craft itself. Only toward the end of the Renaissance, however, did concerns with mensuration and topography become more dominant, as the theoretical universe of these sciences acquired greater specificity. The initial attempt to systematize the processes of measurement appeared in Leone Battista Alberti's *Ludi Matematici*,[55] while the first of a long series of books on the subject appears to have been Cosimo Bartoli's *Del Modo de Misurare le Distantie* (1564), which was followed in 1565 by Silvio Belli's *Libro del Misurar con la Vista*. Belli taught how to measure distances using an instrument, the *quadrato geometrico*, that employed the law of similar triangles.[56]

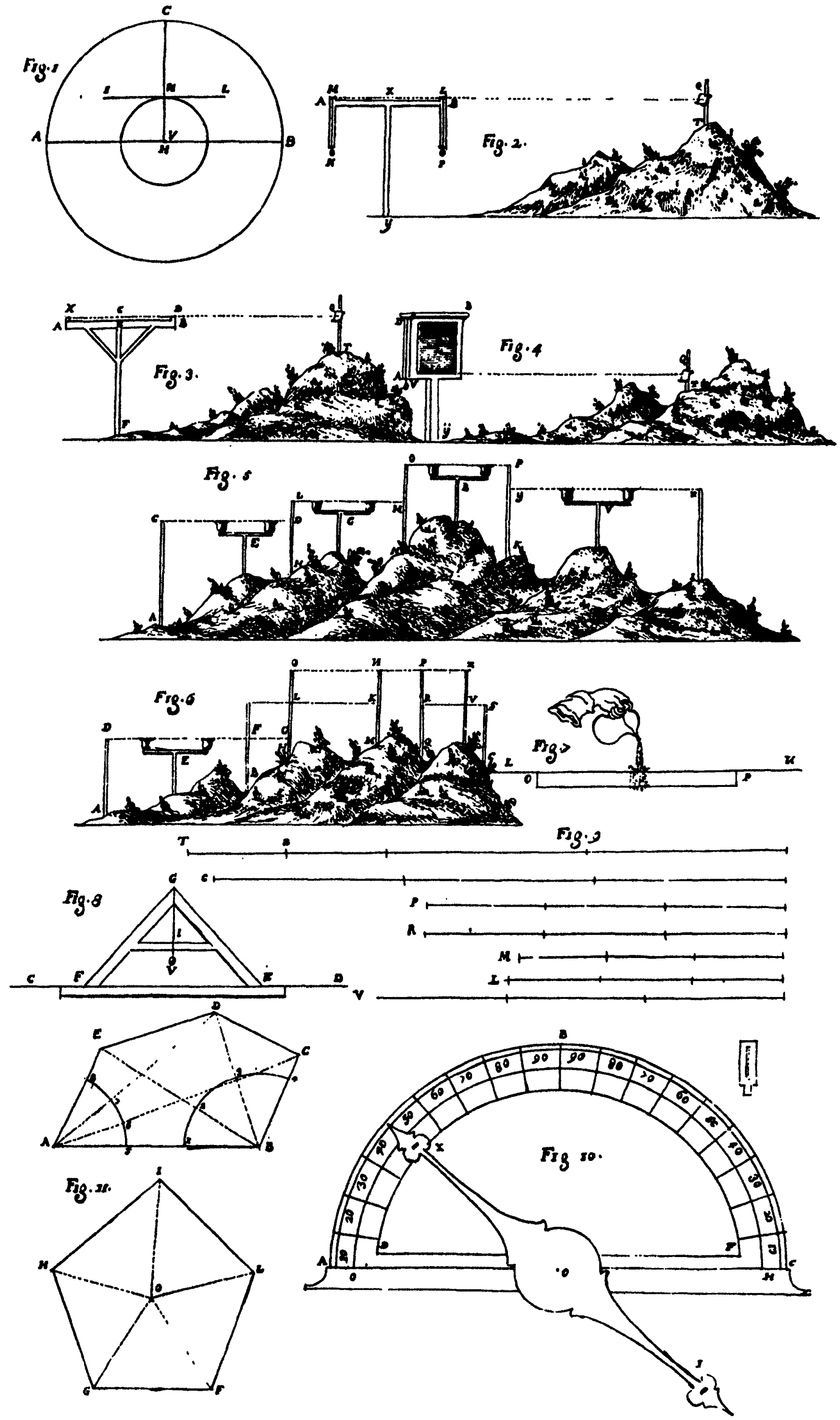
The military engineer G. Cataneo also published a book on mensuration in 1584.[57] His work was unsystematic and practically impossible to apply. But the fundamental purpose of measuring all sorts of areas and volumes and providing methods for surveying was already evident and would be discussed in similar treatises for the next hundred years. Simon Stevin included a section on practical geometry in his *Oeuvres Mathématiques*.[58] Stevin stressed the importance of this science, explaining the special "communion" that existed between extension and number: "What can be done to one, it is also possible to do to the other."[59] He dealt with problems of mensuration in terms of addition, subtraction, multiplication, or division of lines, areas, and volumes. His "arithmetic geometry" was not only a forerunner of Descartes's analytic geometry but also showed how difficult it was to conceive mathematics as an abstract science, devoid of figure and apart from reality.

In the new intellectual atmosphere of the Baroque period, treatises on practical geometry proliferated and were simplified. But the authors of these works never seemed particularly interested in the effective applicability of their theories. The geometry of the seventeenth century, even on this level, basked in an aura of transcendental abstraction. Some texts, as in Stevin's case, were part of universal geometrical systems. Milliet Dechales included in his *Cursus seu Mundus Mathematicus* (1674) a dissertation on practical geometry that was mindful of trigonometry and stereometry.[60] Other authors described specific instruments of measurement; for example, Casati's "proportional compass" and Ozanam's universal "geometrical square," which was capable "of solving all the problems of practical geometry without the use of calculations."[61] Ozanam also wrote in 1684 a comprehensive treatise on practical geometry in which the methods for determining areas and volumes were precise and easily applicable. But this was still not the main concern of his book. Avoiding the exposition of theoretical principles, he revealed a fascination with geometrical exercises. We need only remember here Guarini's reduction of all architectural elements to geometrical figures in his *Modo de Misurare le Fabriche.*[62] All construction techniques were subsumed in a transcendental and universal geometrical science.

Only toward the end of the seventeenth century did treatises on practical geometry begin to reveal an interest to relate it directly and effectively to actual problems of building. Coinciding with the epistemological transformations of this time, the use of geometry and mathematics to solve problems of construction assumed an unprecedented importance—thereafter becoming essential for the success of any building task. Geometry and mensuration ceased to be an end in themselves, but began to be applied as mere tools for the elaboration of construction programs and cost estimates. This transformation was evident initially in the works of Pierre Bullet (1639–1716), one of the first elected members to the Royal Academy of Architecture. His name was frequently associated in the minutes with discussions on technical problems.[63] In 1675 he published *Traité de l'Usage du Pantomètre,* which illustrated the use of an instrument for determining all sorts of topographic angles and accessible and inaccessible distances; and in 1688 he published *Traité du Nivellement,* which provided the theory and practice of another leveling instrument he had invented. Following in the steps of De la Hire, Bullet saw the possibilities in applying the laws of mechanics to architecture and wrote a few papers on the subject.[64]

Bullet's most important work, however, was his *Architecture Pratique,* published initially in 1691 and then quite often during the eighteenth century. This was the first book to provide a concrete application of mathematics to the problems of mensuration and the determination of volumes in all types of building operations.[65] Bullet claimed he had been shocked when he realized that there were no treatises on a subject that was "an absolutely indispensable science for determining with precision the cost of a building." Bullet was familiar with earlier works by Du Cerceau and Louis Savot, which included measurements on the buildings they illustrated and some notions about the determination of volumes of materials, but these were unsystematic operations without a true method.[66]

Bullet acknowledged that the theory of architecture included the principles of proportion (necessary to harmony and decorum), good judgment, drawing, the reading of important authors, the



Surveying operations, from Guarini's *Architettura Civile.*

study of ancient and modern buildings, and mathematics (mainly geometry).[67] But he also insisted that to be an architect, practice was indispensable; it did not suffice to be an *homme des lettres*.[68]

Bullet's *Architecture* started with a general introduction to practical geometry, followed by a careful description of the construction of the typical parts of a building by way of explaining the operations of measurement. A rule based on mechanics was put forward for determining the thickness of a retaining wall in relation to its height and the thrust of the earth. (This was the same problem that had concerned Vauban and whose solution would be reproduced later by Bélidor.) Bullet also considered methods for determining a wooden beam's dimensions and provided a series of rules for finding its depth in relation to the load. But he concluded that due to the infinite qualitative differences among types of wood, such rules could not be absolute.[69] He then provided detailed methods for determining exact quantities of material necessary in each of the building trades: carpentry, masonry, plumbing, glazing, locksmithing, paving, roofing, and so forth. Bullet discussed legal problems, explained building regulations, and finished his book with an illustration of *devis*, that is, detailed specifications and cost estimates for one specific example.

Bullet's architectural intentions were essentially identical to Vauban's and Bélidor's concerns in military engineering. The implications of this reduction of practice to a conceptual program should be apparent. *Architecture Pratique* represented the first attempt to teach methods leading to the establishment of precise construction programs based on quantitative data, including costs, general and particular specifications, and building systems.

In the area of civil engineering, H. Gautier in his *Traité des Ponts* (1714) voiced similar interests. Precision in the design and a comprehensive *devis* were considered extremely important for the successful construction of bridges.[70] The reader may recall how this concern in fact prompted the foundation of Perronet's office.[71] During the second half of the century, Perronet's own projects were considered exemplary for their exactness and for taking into account many and diverse factors.

During the Enlightenment, mathematics was seen only as a practical tool in texts concerned with building techniques, and its instrumental value in construction programs was recognized by most French architects. The general interest in technical problems and the quantitative methods needed to solve these problems increased considerably throughout the eighteenth century. The works by Frezier, Patte, and Potain, and also D'Aviler's *Cours d'Architecture* (1696), Jacques-François Blondel's *De La Distribution des Maisons* (1737), Jambert's *Architecture Moderne* (1764), and another book of the same title attributed to Briseux (1728), are only a few among the many treatises on civil architecture that were concerned with the quality of building materials, foundations, specifications, building systems, or structural soundness and efficiency.[72] Many articles touching upon the building trades appeared in Diderot's *Encyclopédie*, and the Academy of Science continued a systematic study of the crafts that it had begun in the late seventeenth century.

It should be noted that practical geometry and mathematics were not used in the same way in systematic construction programs outside France. Geometrical operations always retained some measure of symbolic power.[73] New treatises on surveying and mensuration, very similar in spirit and content to books of the Baroque period, were published in Italy throughout the eighteenth century.[74] And though G. A. Alberti dealt with more complex problems in his *Trattato della Misura delle Fabbriche* (1757),[75] his lack of interest in the applicability of theory to the solution of real technical problems was nevertheless conspicuous. In many of these books, the traditional connotations of geometry still appeared, often incoherently. G. F. Cristiani, for example, published a text on "the usefulness and delight" of models in military architecture. After mentioning Bélidor, Galileo, Leibniz, Descartes, and the virtues of geometrical calculations and physical experiments, Cristiani emphasized (as did Ricatti) the harmonic structure of perception and the human body. Hence he opted for the "necessity" of employing scale models in fortification.[76]

In England, William Halfpenny used geometrical projections to determine the configuration of all sorts of arches and vaults in his *Art of Sound Building* (1725).[77] He complained about the constant mistakes incessantly committed in practice and provided a careful explanation of brick construction. In *The Modern Builder's Assistant* (1757), he included a catalog with a detailed description of projects, but his cost estimates were very general, not unlike those produced by Du Cerceau in the sixteenth century.[78]

During the second half of the eighteenth century more empirical subjects, such as the application of appropriate methods of measurement and a more precise determination of the areas and volumes of geometry, began to be taught in the French technical schools. This led to the production of eminently quantitative *devis*, which became increasingly effective instruments of technical domination in architecture and engineering. Eventually, the rational planning and programming of construction became the basis of building operations in the industrialized world. The culmination of this process, however, would only take place during the early nineteenth century when the science of measurement and geometrical drawing, the two disciplines that could implement the reduction of the reality of building practice to two dimensions, had become sufficiently systematized.

Stereotomy

Stereotomy, the use of geometric projections in determining the shape and dimensions of stone or wooden elements in arches, vaults, trusses, stairs, and domes, was specifically a French concern. It was initially incorporated in Philibert de l'Orme's *Architecture* (1567), the first original architectural treatise published in that country to show a Renaissance influence. De l'Orme devoted several chapters of his book to illustrate the use of horizontal and vertical projections in determining in two dimensions the precise configuration of complex parts of buildings. This method of simultaneous projections was never used before the Renaissance. Dürer used similar techniques in his studies on the human body in 1528 and in his research on conic sections in 1525.[79] Generally, however, stereotomy was not an effective technical method during the sixteenth century. Of the problems studied by De l'Orme, for example, the solutions were so specific that it is impossible to understand them at a merely conceptual level. The fundamental dimension was still the Gothic craftsmen's experience. Without it theory was useless, and even with such experience, theory was practically irrelevant to technique. The plates illustrating the use of projections in De l'Orme's *Architecture* did not constitute a method; they did not derive from a general geometrical theory capable of generalizing specific solutions of specific problems.

Several works on stereotomy were written during the seventeenth century. In 1642, Mathurin Jousse published *Le Secret de l'Architecture*, in which he claimed that although he admired the buildings of antiquity, many of them failed to fulfill one's expectations because they were built by craftsmen who ignored the necessary geometrical tracings for stonecutting.[80] He was aware that neither Vitruvius nor Renaissance authors had written on the subject and believed that De l'Orme's two chapters were too complicated for craftsmen. His own work was therefore intentionally simple, reducing to the minimum the elements of each problem and the lines of projection. But in his attempt to provide a strictly useful technical instrument for carpenters and stonecutters, he produced, in fact, a work that was incapable of coming to terms with the real complexity of the problems.

In accordance with his interest in technical problems related to construction, Jousse encouraged young architects to study arithmetic, geometry, dynamics, and statics. In his *L'Art de la Charpenterie*, he provided geometrical descriptions of all sorts of trusses, centering, and roofing and a complete catalog of all known elements for wood construction. Although there were no explicit symbolic intentions in Jousse's use of practical geometry, he referred to carpentry as the art of original architectural ornament; and above all, he believed that the exposition of the craftsman's geometry was like the revelation of a transcendent secret: the essential *modus operandi* of architecture. These echoes of the late medieval world were obviously in perfect accord with the implications of the Baroque geometrization of the cosmos.

The Jesuit François Derand published in 1643 *L'Architecture des Voûtes*. Much more extensive, specialized, and ambitious than the works of his predecessors, this treatise was intended both for architects and craftsmen. Derand maintained that to learn stereotomy, practice was indispensable. It was not sufficient only to read about it because in the mechanical arts, "practice is not invariably linked to the laws of rigorous geometry."[81] His book included tracings for all sorts of masonry works and their geometric projections. Derand used a more specific technical language than previous authors. An understanding of his work demanded a knowledge of geometry, careful and systematic reading, and constant practice. The solutions of the problems were, nevertheless, very similar to those proposed by De l'Orme, whose *Architecture* Derand frequently cited.

Dechales also included stereotomy in his *Cursus seu Mundus Mathematicus*, as one more discipline subject to the transcendent order of a universal geometry.[82] A considerable section on this science was an important part of Guarini's *Architettura Civile* and was taken fundamentally from Derand's treatise. The symbolic concern underlying Guarini's interest in stereotomy is now evident. Also, François Blondel included problems of stereotomy among the "principal" and most difficult in architecture.[83]

During the seventeenth century, there were no autonomous techniques claiming to derive their value from efficiency or applying their specific parameters to decision making in architecture.

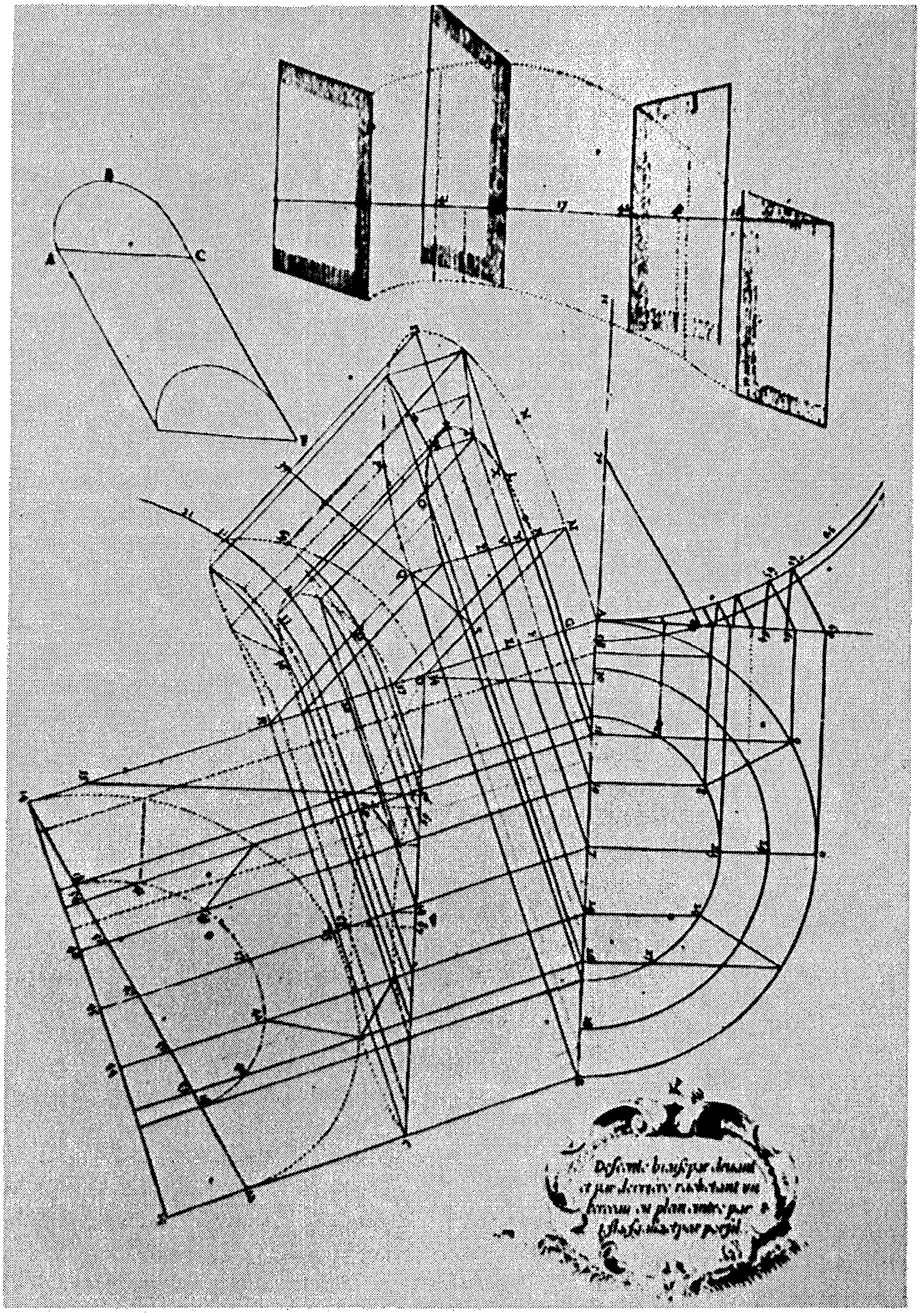
The geometry implicit in vault construction and other stereotomic marvels constituted, like the mathematical order of a fugue, both the structure of the work and the ultimate source of its meaning. The description of geometrical projections in treatises was the elucidation of an eminently symbolic (that is, poetic) operation.

The great exception to this rule appeared, perhaps not surprisingly, in the work so far ahead of its time of G. Desargues. Stereotomy was one of the disciplines for which his universal geometrical method would serve as the foundation. He established the theoretical principles of his "universal manner" in the *Brouillon-Project,* a small pamphlet published in 1640. This was followed by a more extensive treatise on stonecutting published by Bosse in 1643.[84]

While Derand's *Architecture des Voûtes* was still being published in 1743 and 1755, Desargues's *Brouillon-Project,* containing the basic postulates of projective geometry, remained unknown until the nineteenth century. It is clear that masons and architects could not comprehend Desargues's attempt to replace practice by an all-embracing general theory. In *La Pratique du Trait . . . pour la Coupe des Pierres,* Desargues indicated that "the means to do something" were an essential part of any art. Theory, in his opinion, had to include an explanation of these technical means and not only an elucidation of the art's objectives. These technical means could be "exact, developed through reason," or imprecise, deriving from approximation and the intuition of craftsmen. Desargues was the first to argue so strongly for the need to implement exact technical means.

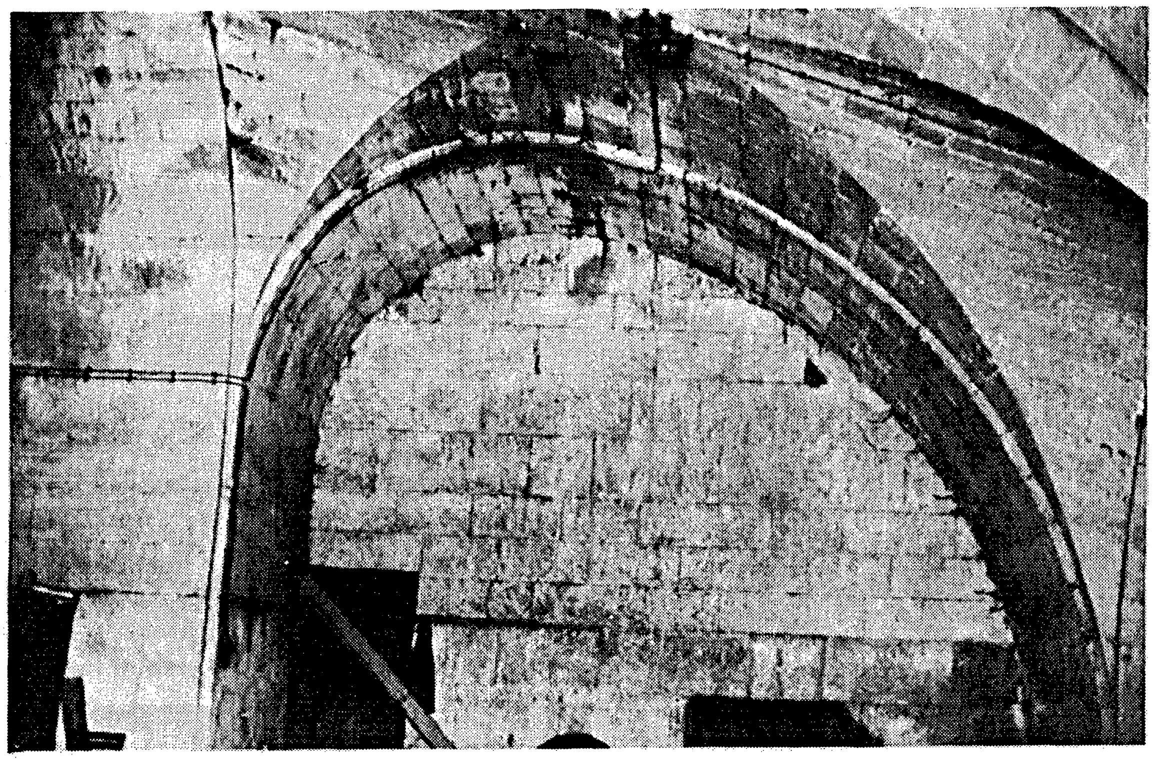
He believed that in order to invent the rules of any art, one should know its "reasons," but it was not always necessary to be a craftsman. This assertion contrasts sharply with the commonplace acceptance of the role of practice as propounded by Jousse or Derand. Desargues recognized three aspects in any activity, all important, but ordered hierarchically: first, the theory—a framework in which to invent and establish the rules of practice; second, the rules themselves, derived directly from theory; and third, practice—the execution of these rules, somehow inferior, obliged to follow strictly the prescriptions of theory.

Desargues was conscious of the fact that no one before him had reduced the art of stonecutting to a set of methodical and universal principles. He pointed out that other treatises had only solved specific problems relating to the times in which they were written. Alluding to Jousse, Desargues reminded his readers that not long ago each projection and tracing was "considered a secret



Geometric projections applied to the stereotomic description of a vault, from F. Derand's *L'Architecture des Voûtes* (1643).

Stereotomic virtuosity in the vaulting of the *orangerie* in the Palace of Versailles, designed by J. H. Mansart (1681–1686).



that had to be learned by heart. . . ."[85] He proposed instead a simple and unique method that could be used to solve *any* problem. It sufficed to follow a set of step-by-step rules, regardless of the operator's firsthand knowledge of the craft. Desargues thought that the architect should provide the craftsmen with precise stereotomic tracings to cut every piece of stone, just as he provided plans, sections, and elevations. Architects should never allow the masons to invent these tracings since they had nothing more to go on than their own experience.

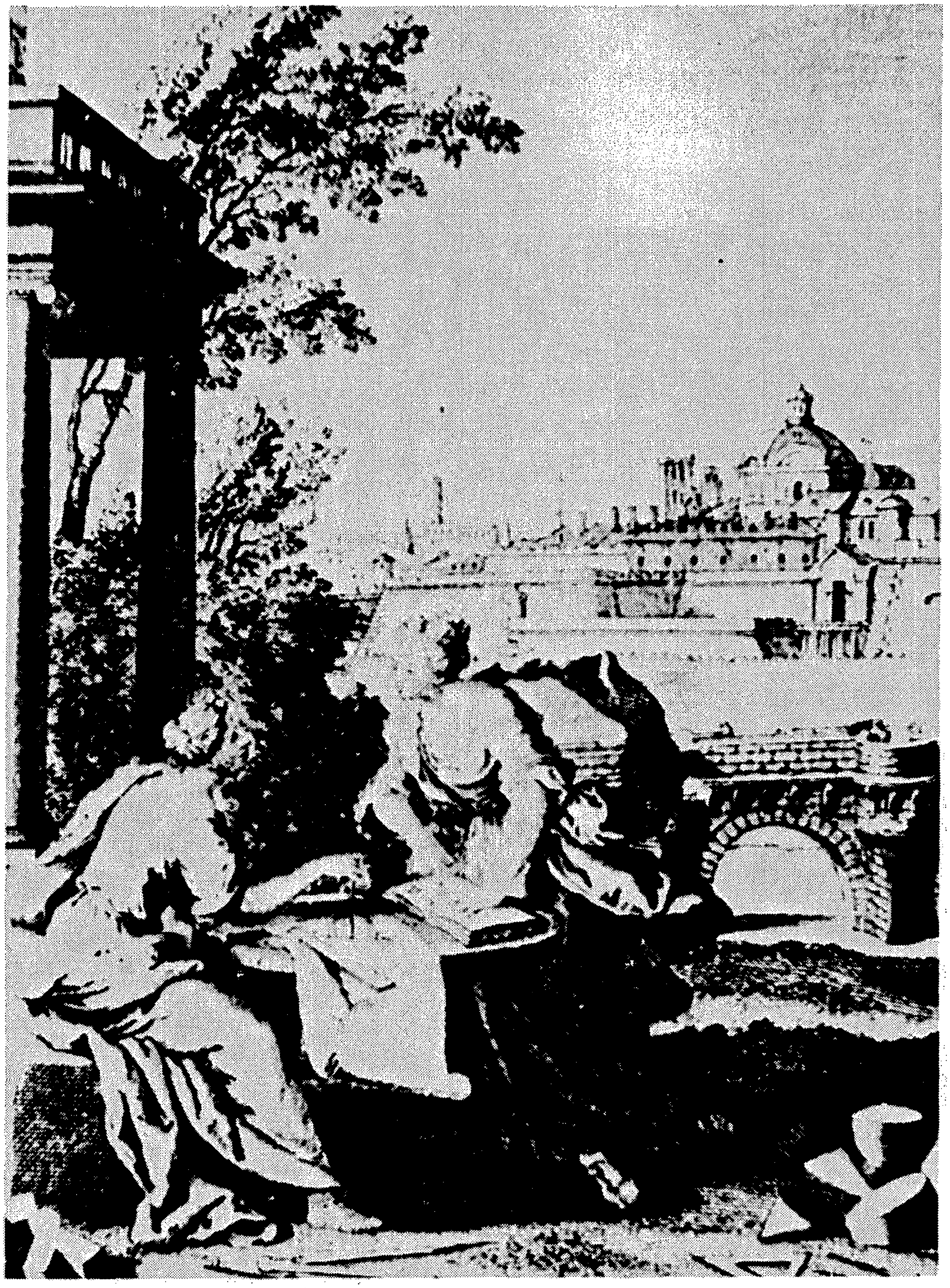
During the last decade of the seventeenth century and the beginning of the eighteenth century, there were some discussions about stereotomy in the academy.[86] But generally speaking, the architects of the Enlightenment, in contrast to their Baroque predecessors, were not interested in geometrical projections. The only important work on stereotomy written during the eighteenth century was Amédée-François Frezier's *La Théorie et la Pratique de la Coupe des Pierres et des Bois* (1737). Frezier was a highly regarded military engineer and in 1712 was made responsible for the construction of several French fortifications in Europe. His was one of the textbooks recommended by D'Asfeld to the students at Mezières.

Frezier wrote his book believing that theory was the "soul" of both the arts and the sciences. His interest was to elucidate the "geometrical reasons of tracings used in architecture" because this dealt with the most difficult part of practice, namely, the "exactness, solidity, and propriety" of all types of vaults.[87] Three preliminary dissertations preceded this voluminous work. In the first, Frezier proved the "usefulness of theory in the arts related to architecture" by arguments very similar to those used by Bélidor in his *Science*. He emphasized the importance of theory as a technical instrument and its effectiveness in practice—something denied by most of his contemporaries. Frezier stressed that we should not wait for practice to teach us and that reflection and theory hastened the way to the solution of problems. His objective was to provide a different route from that of other authors, who had considered stereotomy from a standpoint "too close" to practice.

Unlike seventeenth-century architects, Frezier felt that he had to *justify* his interest in geometry, citing examples drawn from *mechanics*. Frezier claimed that before geometry and mechanics had been applied to architecture, the structural soundness of vaults was not assured; they lasted only a short time and had to be demolished, were not pleasant to behold, or, because the dimensions of their supports were exaggerated, were unnecessarily expensive.[88] With regard to construction, Frezier adopted De la Hire's hypothesis, thereby showing that he understood how statics could be applied to architecture and engineering. He rejected seventeenth-century geometrical methods for determining the dimensions of piers and emphasized the importance of mechanics as an example of a truly effective and indispensable theory of architecture. The associations established by Frezier between a theory conceived as *ars fabricandi* and the geometrical theories of statics underscore his comprehension of mechanics as the paradigmatic modern science. His interest in geometry arose from his perception of mechanics as an instrument capable of controlling matter—not, as had been the case among his predecessors, from a belief in the immanent symbolic attributes of geometrical operations.

Frezier stressed that military engineers should be cognizant of geometry, mechanics, and hydraulics when planning their attacks or building fortifications. Stereotomy was indispensable not only for them but for architects as well. He criticized earlier treatises for not being sufficiently methodical and, with the exception of Derand's book, for presenting the subject matter only to craftsmen. What was needed was a book for architects and engineers who already knew something about geometry. Significantly, Frezier had to conclude his first dissertation with the admission that the "natural geometry" of the craftsman was usually enough to solve most problems of stone- or woodcutting. His theoretical *tour de force* was therefore rendered ineffective by a traditional practice that was for the most part still successful. Indeed, this was the paradox faced by most eighteenth-century theoreticians. Nevertheless, Frezier believed in the importance of providing a method that would allow the architect to solve any stereotomic problem, regardless of its complexity. This, once again, attests to the architect's interest in technological control, which originally was motivated by the epistemological revolution, and which appeared in the sphere of theory long before its effective implementation during the nineteenth century.

Frezier's intention, therefore, was to postulate a general theory of stonecutting as an autonomous technique that could direct the craftsman's work in the execution of any structural element of a building capable of being treated as an aggregate of smaller pieces. And its principles are necessarily derived from geometry, mechanics, and statics. Frezier's first volume was devoted to geo-



The uses of geometry, an allegory on the cover page of Frezier's treatise on stereotomy (by courtesy of *Daidalos*, Berlin).

metrical theory and discussed conic sections, intersections of solid bodies, properties of all types of curves, projections on flat and spheric surfaces of arches and vaults, and a method for finding the voussoir's angles. The text, full of neologisms and technical terms, often criticized the absence of principles in previous works on the subject. It is important to note, however, that Frezier only referred briefly to Bosse's *La Pratique du Trait* as "a totally different system" that had been derived from Desargues's and that had never become popular.[89]

In fact, two full volumes of Frezier's treatise were devoted to practical applications. But in spite of his intentions, his theory was not truly systematic and universal; it never went beyond Euclidean geometry and was therefore limited to specifics. Each example ultimately depended on intuition and the particular properties of the figures or bodies involved. The complexity of the operations involved in treating these figures and bodies within the framework of Euclidean geometry amounted to a dead end. And because the exercises were hardly related to the much more simple problems of conventional practice, his book was not used by architects, engineers, or craftsmen. The editor of the 1760s version of D'Aviler's popular *Cours d'Architecture* included a small section on stereotomy in which he criticized Desargues, "who hid all that he wanted to teach," and Frezier, whose book he found extremely complicated. He recommended instead Derand's *Architecture des Voûtes* because in stonecutting, "practice is preferable to theory."[90]

Frezier's book seemed to be addressed to some imaginary *virtuosi* who might find pleasure in mathematical complexity. In any case, it is clear from Frezier's interest in proportion and the classical orders, and from the polemic in which he supported Patte's criticism of Soufflot's mathematical determinism, that he still perceived *mathemata* not only as a source of stability or durability but also, however ambiguously, as the ultimate origin of beauty.[91] It could be concluded, therefore, that with the exception of Desargues's work, the relation between the theory and practice of stereotomy did not effectively change during the seventeenth and eighteenth centuries. The problems of projection were indeed solved in different ways by different authors, each of whom employed manifold graphic systems. But these techniques were not capable of sufficient precision; and the reduction of three-dimensional reality to the plane was never really thorough enough to provide an effective, rational control over stone- or woodcutting operations.

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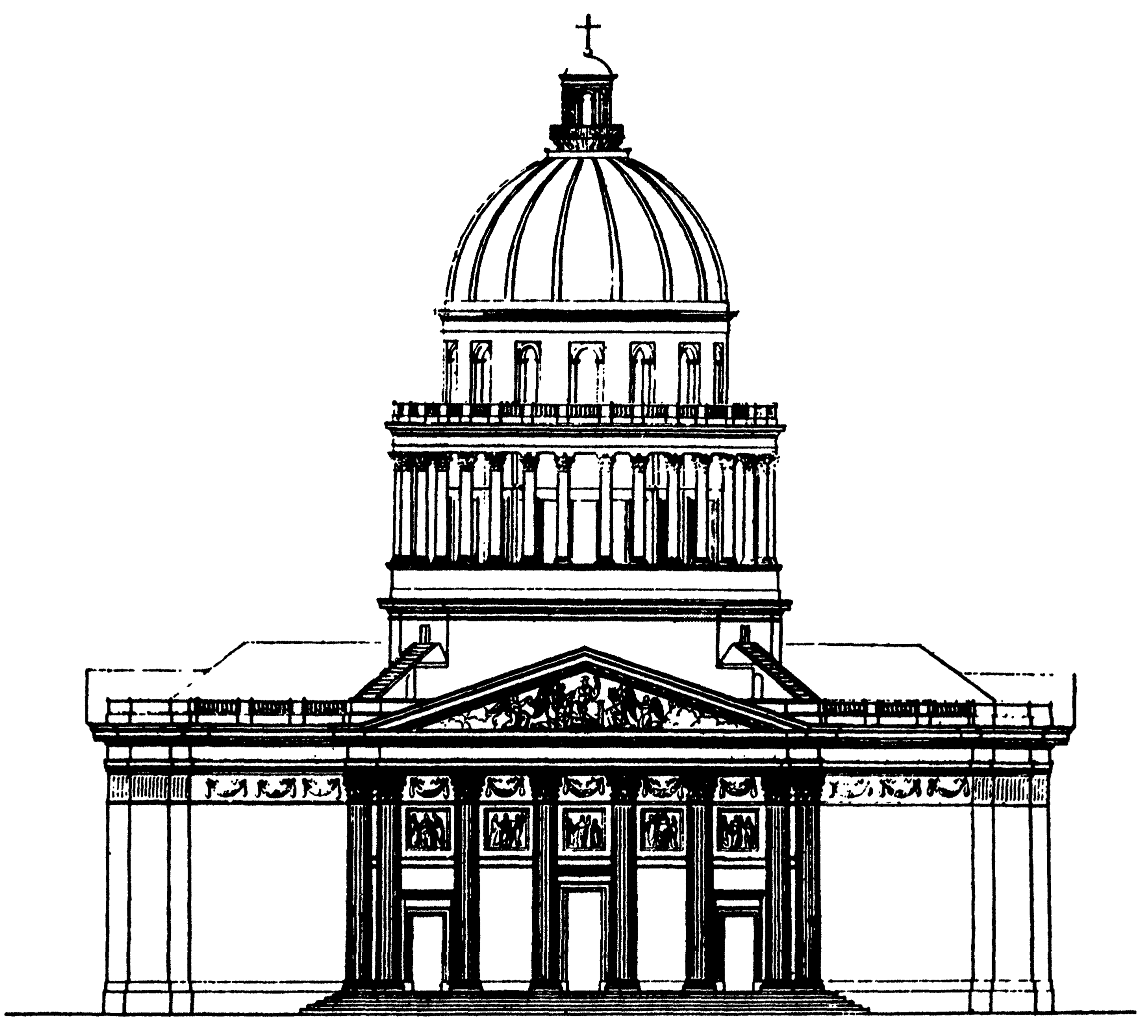
STATICS AND STRENGTH OF MATERIALS



The reorganization of the heavens by Copernicus and Galileo brought about not only a transformation of Western man's intellectual sensibility but also a dislocation of his place in relation to reality. The most fundamental presuppositions of mental space were reversed. Simple events of everyday life, particularly motion, began to be conceived as much more complex phenomena. Robert Boyle defined nature as "the inventory of bodies which constitute the world in their present state, considered as a principle by virtue of which they are active or passive, according to the laws of movement prescribed by the Author of all things."[1] For Leibniz, the world was also a *Horologium Dei*.[2] The degree to which mechanics became the essential discipline for a knowledge of nature affected the necessity of divine intervention in epistemology. And it was precisely in the field of mechanics—defined by Boyle as "the application of mathematics to produce or modify movement in the bodies"—that number conceived as a technical instrument merged with natural science, thereby producing the first functionalization of reality, and endowing the human mind with an effective power to dominate matter.[3]

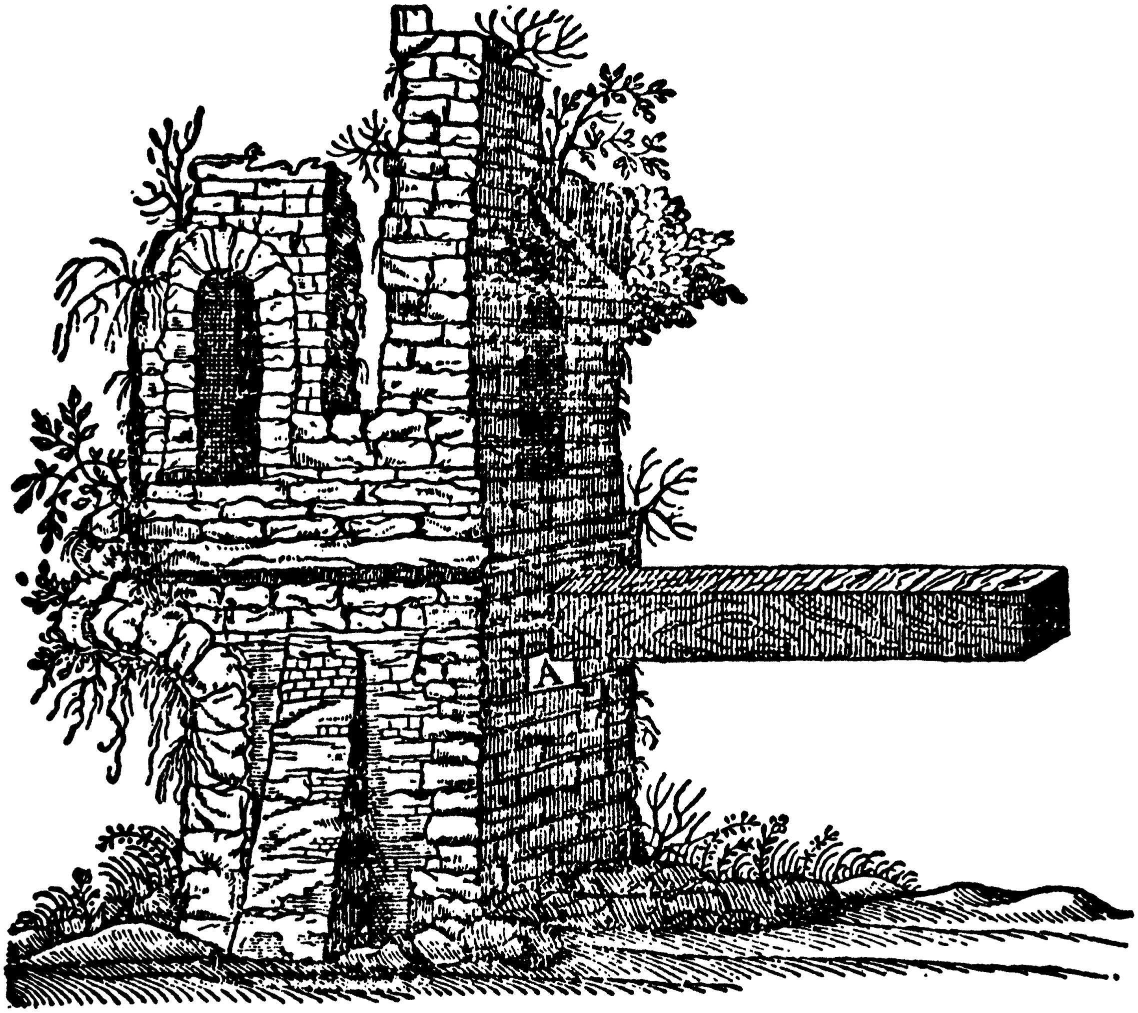
Mechanics, as is well known, is comprised not only of dynamics but also (and of greater interest for architecture) statics: the analysis of bodies in a state of rest or equilibrium. Apart from the rare speculations of Leonardo da Vinci about forces acting on structural members, Simon Stevin was the first to try to understand, geometrically, some basic problems of mechanical equilibrium. A chapter on statics in his *Oeuvres Mathématiques* (1584) analyzes the forces acting upon a body on an inclined plane. Stevin declared that this science was incapable of considering such factors as friction or cohesion. The force needed to move a cart was obviously greater than that which resulted from a theoretical calculation. But the discrepancy, according to Stevin, was not the fault of science. Like Kepler, Stevin accepted the traditional distance between geometry and reality. His application of this science to the sublunar world was obviously an innovation, but his work was still an elucidation of the geometrical behavior of reality. Stevin did not believe that a connection between geometrical hypothesis and the mutable world of reality was necessary; even less necessary was a reduction of the latter to mathematical operations.

Only Galileo formulated clearly the problems of statics and strength of materials as part of the total geometrization of human space: To determine, by means of a geometrical hypothesis, the dimensions of structural elements in relation to the weights they had to carry and the quantitative properties of the building materials. The application of geometry to mechanics thus revealed from the very beginning an intention of technical control. As the world was transformed into *res extensa* (number and figure), man discovered the power of his rational mind to control and exploit nature.

During the seventeenth century, mechanics was essentially the concern of philosophers, scientists, and geometricians, particularly after the foundation of the scientific academies in the 1660s. In a historical introduction to a treatise on strength of materials published in 1798, P. S. Girard attributed the first quantitative experiments in this science to a Swede, P. Wurtzius. He said that he had obtained this information from a letter that Wurtzius had addressed to François Blondel in 1657. Girard referred to a work by Blondel entitled *Galilaeus Promotus* and indicated that the French architect had been the second to write on the subject after Galileo.

This interest on the part of the founder and first professor of the Royal Academy of Architecture is in itself significant. Blondel's observations on Galileo's hypothesis appeared in the fourth of his "principal" problems of architecture, which provided a geometrical method for determining the dimensions of beams.[4] In the same problem, however, he also discussed the errors of Pappus on harmonic proportion. Blondel's geometrical tracing to determine the dimensions of the piers and buttresses of an arch or vault was taken from Derand's *Architecture des Voûtes* and, although this tracing was concerned with the configuration of the arch in question, it was not based on a mechanical hypothesis.[5] It should be remembered that Blondel's geometry was still, fundamentally, a Baroque universal science.

In this respect, it is interesting to consider *Il Tempio Vaticano e sua Origine*, a book published in 1694 by the successful architect Carlo Fontana.[6] Fontana was convinced that the only way to ensure the stability of domes was to determine their sections by means of complex and precise geometrical tracings. Discussing the structural problems of St. Peter's dome, Fontana superimposed on the section his ideal geometrical tracing to "prove" the dome's soundness. Similar tracings were also used for his designs of doors and frontispieces. This geometry obeyed not the logic of mechanics, but the orders of the architect's imagination, which ensured the meaning of the work: its beauty *and* solidity. This discovery of the geometry "implicit" in St. Peter's design still had



The principle of the cantilever, from Galileo's *Discorsi Intorno à Due Nuove Scienze* (1638).

the character of divine revelation; it endorsed the value of the most important church of Catholicism, whose legendary origin Fontana also disclosed.

Although much of the theory of statics had been developed by scientists and geometricians in the seventeenth century,[7] it was not until the 1680s that there appeared the first true applications of statics to architecture and engineering. I have mentioned the attempts of Vauban and Bullet to determine the dimensions of retaining walls, as well as De la Hire's presentation of these problems in the discussions of the Academy of Architecture after 1688. Bearing this in mind, it should be noted here that De la Hire was the first in a long tradition of architect-geometricians who tried to apply Varignon's general theory of the resolution of forces to the fundamental problem of stability of arches and vaults.[8] It was De la Hire who actually postulated the first truly mechanical hypothesis concerning this problem.

In contrast to prior works on mechanics and automata (for example, De Caus's *Raisons des Forces Mouvantes*), De la Hire's *Traité de Mecanique* (1695) praised the discoveries of Galileo and avoided all allusions to the magical or occult qualities of mechanical effects. De la Hire realized that physical reality did not behave with all the rigor of geometry. Nonetheless, he emphasized that all the arts needed the science of mechanics to assure their success.[9] Concerning arches, he advocated a geometrical method for determining the load that should be taken on by each voussoir in order to fulfill the conditions of equilibrium, assuming no friction between the surfaces of the pieces. This was obviously derived from Varignon's solution to the problem of equilibrium in solid bodies through the resolution of vectors, independently of cohesion or other external factors. De la Hire presented his hypothesis to the architects of the academy in 1712, outlining a concise geometrical method for quantifying the stress produced by the thrust of an arch. Taking into account the height of the piers and the radius, maximum height, and weight of the arch,[10] these calculations would determine the necessary dimensions of the supporting piers.

Although De la Hire believed that geometry was indispensable for all sorts of operations in architecture, not even his position was free from ambiguity. For example, he publicly recommended Ouvrard's treatise on harmonic proportion and in 1702 presented a paper to the Academy of Science in which he tried to prove that many arches used intuitively by architects were in fact pa-

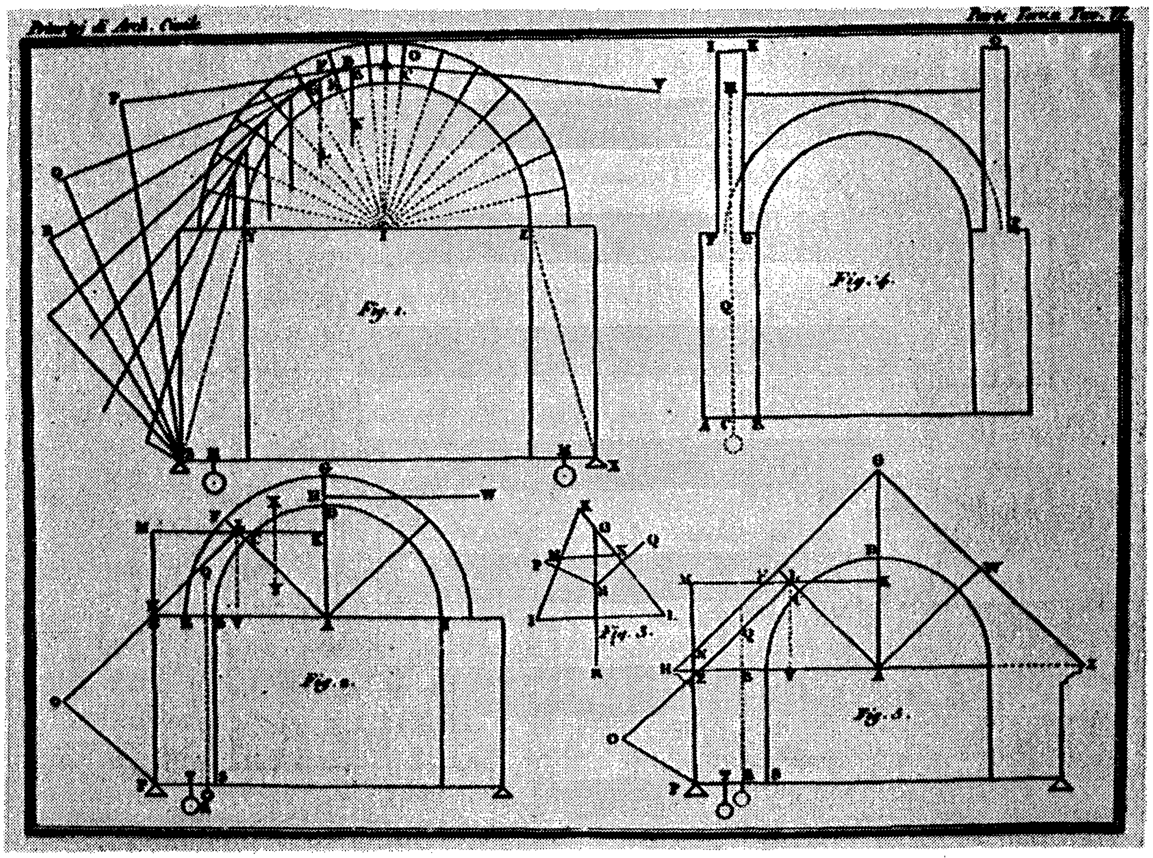


Illustration of De la Hire's hypothesis applied to diverse problems in the design of arches, from F. Milizia's *Architettura Civile* (1781).

rabolas, more agreeable in their proportions than sections of circles or ellipses.[11] (Editing this paper, Fontenelle remarked how geometry, although in itself "boring and dry," had corrected an "invention" whose only purpose was to please the eye.)

Similar ambiguities appeared in Pitot's paper *Sur la Force des Cintres*, which was presented to the Academy of Science in 1726. Making use of data on the resistance of wood and Varignon's theory, Pitot found the corresponding stresses in the parts of a wooden scaffold and was able to determine their thicknesses given their angles. His intention was to quantify the "correct proportions," reduce the number of members, and improve their connections. And yet Pitot too believed that the geometry of statics also produced a disposition that was sometimes more agreeable to the sight.[12]

H. Gautier, an "architect, engineer, and inspector" of the recently formed *Corps des Ponts et Chaussées*, was the author of the first specialized treatise on bridges written by a "professional." The first part was traditional; it listed and compared famous old and existing structures and the models proposed by Alberti or Palladio. His advice was generally empirical. There was an explanation of technical terms and of the regulations of the *Corps des Ponts et Chaussées*, an example of *devis*, and the rules of Vauban for determining the dimensions of retaining walls.[13] But in the dissertation on the piers, voussoirs, and thrusts of bridges added to the second edition of his *Traité* (1727), he discussed problems of statics and strength of materials.[14] Familiar with recent contributions in this field, Gautier tried to apply them to bridge construction. He believed that the arts, particularly architecture, were "founded on mechanics," which, being a part of mathematics, was liable to rigorous demonstration. Regardless of its origin, proportion was, in Gautier's opinion, the most difficult part of architecture, on which a consensus was still lacking. Although he recognized that mechanics was needed to establish definitive rules of proportion in architecture, he openly rejected De la Hire's hypothesis, considering it too complex and divorced from practice. Instead, he applied the simple geometrical tracings of Derand and Blondel to determine the dimensions of piers in bridges. He also emphasized the need of quantitative experiments in strength of materials, but was seemingly unable to distinguish between geometrical methods and truly mechanical hypotheses. He obviously considered the seventeenth-century tracings more practical for craftsmen and, indeed, more in keeping with traditional practice.

Most French engineers and architects of the Enlightenment, however, did accept De la Hire's theory with a greater or lesser awareness of the problems resulting from the distance between geometrical hypotheses and real phenomena. And De la Hire's fundamental intention was in fact shared by all. Bélidor and Frezier used his hypothesis in their texts on building and stereotomy, while scientists like Parent and Couplet incorporated it in papers on the equilibrium of vaults during the first thirty years of the century.[15]

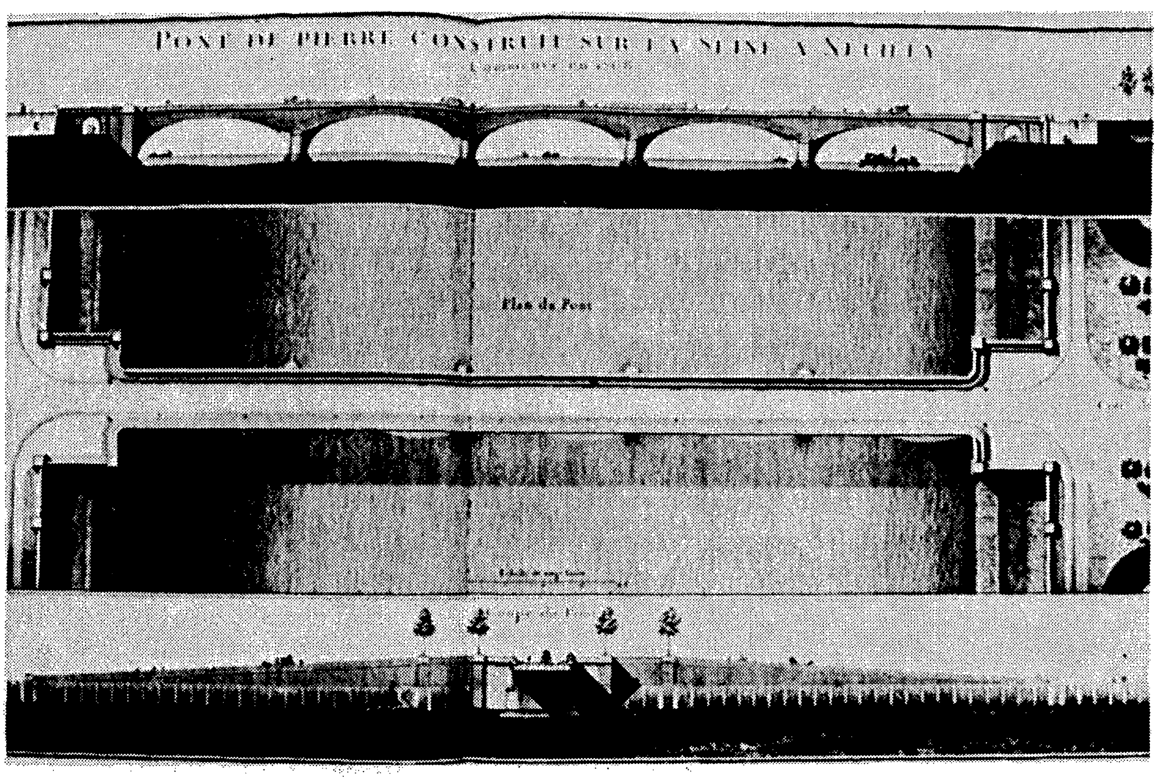
The first half of the eighteenth century also witnessed the beginning of systematic experiments on the strength of materials. Following in the steps of Mariotte, who had reported some isolated tests in the previous century, Parent presented a paper to the Academy of Science on the strength of wood in 1707; and in 1711 Reaumur read a piece on the resistance of steel wire.[16] Bélidor's treatise was the first book on construction to include the quantitative results of experiments on the strength of the wood normally used for beams. Inspired by the new empirical method of Newton, Musschonbrek published in 1729 *Physicae Experimentales et Geometricae,* which included several machines of his own invention for testing stresses in various materials. The text reveals that he was much more methodical and precise than his predecessors. Similarly, Buffon tested wooden beams of all sizes, including full-scale specimens. According to Girard, Buffon was the first to consider all the important factors affecting the strength of wood (for example, the way a tree had been felled or its humidity content). Such systematic observations took on a greater significance for architecture and engineering during the second half of the century.

Around 1750 the quantitative results of experiments seemed to have taken priority over geometrical hypotheses in the minds of those architects and engineers who were concerned with structural problems. The work of Jean-Rodolphe Perronet, founder of the *École des Ponts et Chaussées* is highly significant in this respect. His quantitative observations regarding the structural behavior of bridges and his systematization of construction methods had a great influence on his contemporaries and became absolutely indispensable toward the end of the eighteenth century in correcting the old theories on statics. His own bridge projects were the first in which a consideration of the materials' mechanical behavior was attempted. In *Description des Projects* (1782), a splendid collection documenting some of his works, he described in great detail and with precise engravings the construction of the famous bridge at Neuilly. The project was in fact an engineering masterpiece. Nothing was left to chance; every building stage was carefully planned, including the specific quality of materials, special machinery, the dimensions of each detail, and even the number of workers to be employed at each phase.

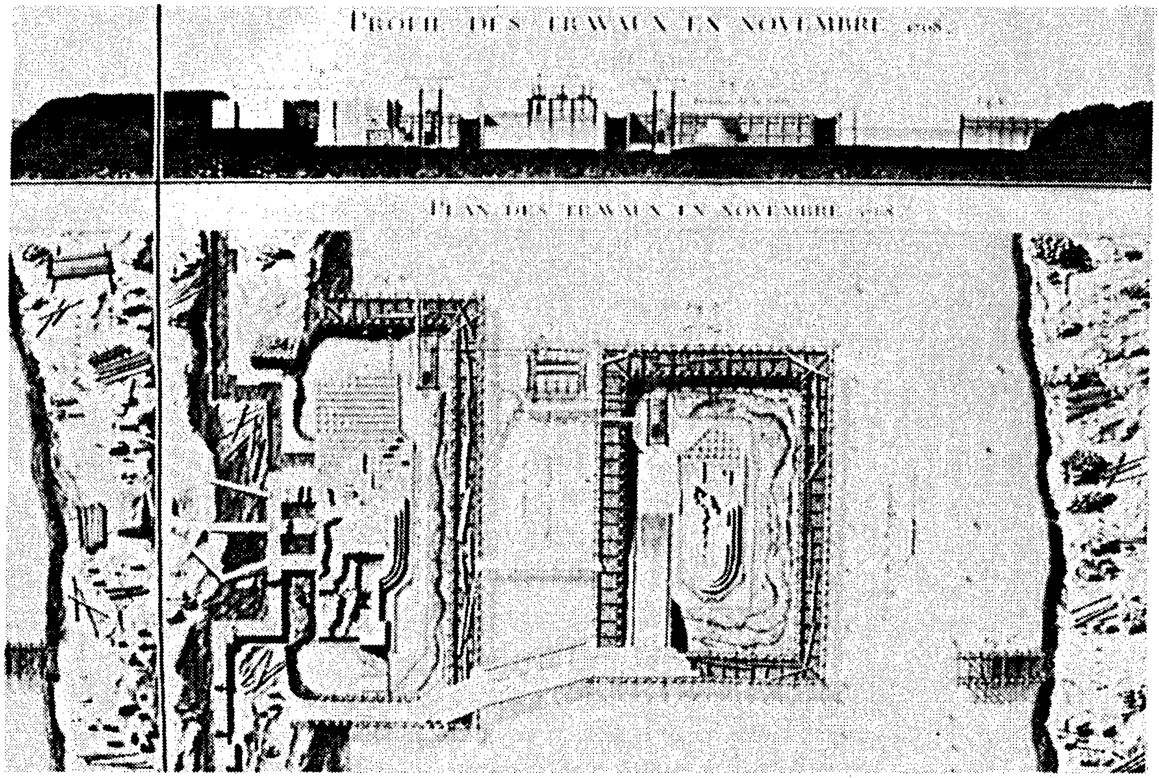
Perronet clearly attached great importance to observation and adopted the empirical method of natural science to engineering. Therefore it is almost paradoxical that Perronet's general advice to his students appears to be more conservative than that of his predecessors'. Following upon his comprehensive discussions, he finally decided that his own experience was more valuable than the results of calculations. Theory, he wrote, is insufficient; a successful practice is the surest guide.[17]

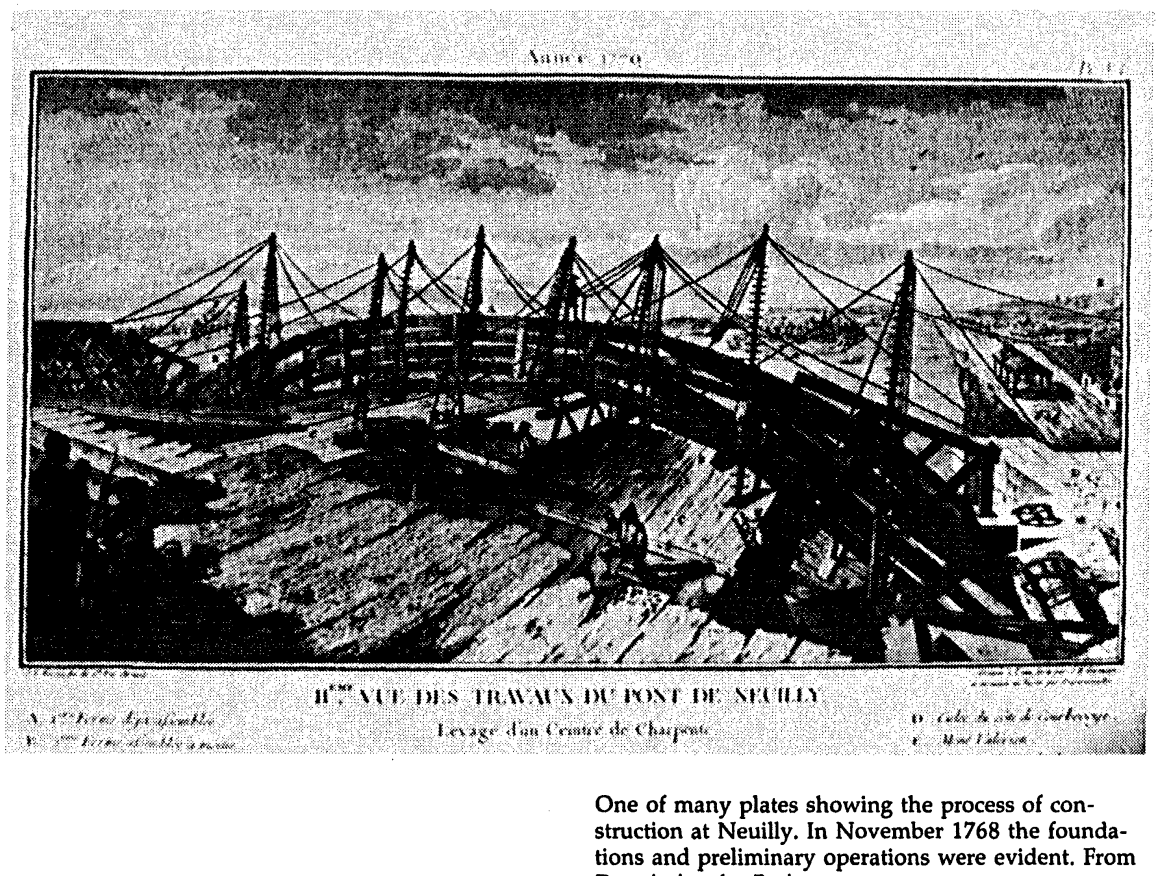
Perronet's *Description des Projects* was not an analytical treatise on bridge construction. It was essentially an attempt to teach by examples, and in this it was not unlike the didactic methods used at the *École des Ponts et Chaussées*. The text was an amalgam of the author's experiences and quantitative data organized systematically. It is perhaps significant to note how limited Perronet's contributions were to the Royal Academy of Science.[18] For although Perronet demonstrated a full understanding of mechanical effects—such as the role of piers as buttresses, the advantages of reducing the mass of such piers to allow a freer flow of water and save material, and the greater thrust of lower basket arches—his well-known preference for this latter type of arch over the traditional semicircular one was justified only in terms of common sense.[19] And while he acknowledged the results of experiments on the strength of stone, "such as those realized by Soufflot at Saillancourt," which suggested the possibility of considerably reducing the dimensions of the piers—traditionally one fifth of the span—Perronet did not provide geometrical methods or equations to apply in actuality the quantitative data derived from experiments to structural design. On the contrary, he believed that his rules, based on his own experience, were far superior. Thus in spite of "the great strength of the stone," he advised his students to continue using simple arithmetic proportions to determine the dimensions of all parts of a bridge—a method reminiscent of the most traditional Renaissance rules of thumb.[20]

Perronet stressed the importance of quantitative experiments in other academic papers.[21] With regard to methods of laying a foundation, he mentioned the experiments of Musschonbrek, Buffon, Parent, and Gautier, but finished by providing simple recipes in terms of the duplication, triplication, or division of the diameter



Plan and elevation of Perronet's bridge at Neuilly, from *Description des Projets*.





One of many plates showing the process of construction at Neuilly. In November 1768 the foundations and preliminary operations were evident. From *Description des Projets.*

View of the scaffolding for one of the arches of the bridge at Neuilly during 1770, from *Description des Projets.*

of piles, according to their own weight and other dimensions of the structure. Although his recommendations were linked to experimental observations, the quantitative results were not translated into mathematical analysis. Everyhing was summarized in a conventional discourse in which the experimental results were subsidiary to his own experience in building.

Tradition and Mechanics in Italian Architecture

The application of statics by French scientists, architects, and engineers in the early eighteenth century did not go unnoticed by the rest of Europe. Particularly in Italy, there appeared original interpretations that merit attention. In 1748 Giovanni Poleni published his famous work in which he recapitulated the debate concerning the structural problems of St. Peter's Basilica in the Vatican.[22] The dome had been deteriorating for some time, as Fontana had already pointed out. But the cracks became more dramatic after 1742, and many mathematicians, architects, and engineers wrote papers in an attempt to diagnose and solve the problem. Poleni, after providing a history of the church, then unfolded his own ideas about mechanics.

He declared that the application of mechanics to architecture was impossible without mathematics and that it presented the greatest difficulty when focused on the building of arches and domes. Mentioning the "geometrical methods" of Derand and Blondel and the "occult geometrical rules" of Fontana, he dismissed their contributions "for not being adapted to the mechanical properties of building materials."[23] Thus Poleni distinguished between the traditional use of geometry as it appeared in seventeenth-century treatises and its potential as a technical instrument in mechanical hypotheses. Also mentioned were the contributions of De la Hire, Parent, and Couplet, as well as Gregory's analysis of the catenary, which had been published in Britain in 1697. Gregory's work was based on Robert Hooke's discovery about this curve's properties of ideal stability and additionally assumed a direct transmission of forces among frictionless voussoirs. The shape of a freely suspended chain would then be the ideal configuration for a masonry vault or arch, and Poleni superimposed one on a section of St. Peter's dome, believing that because the tracing fell within the mass of the structure, the dome's stability was guaranteed.[24]

Poleni described the structural problems of other well-known domes before going on to discuss reports and analyses by various

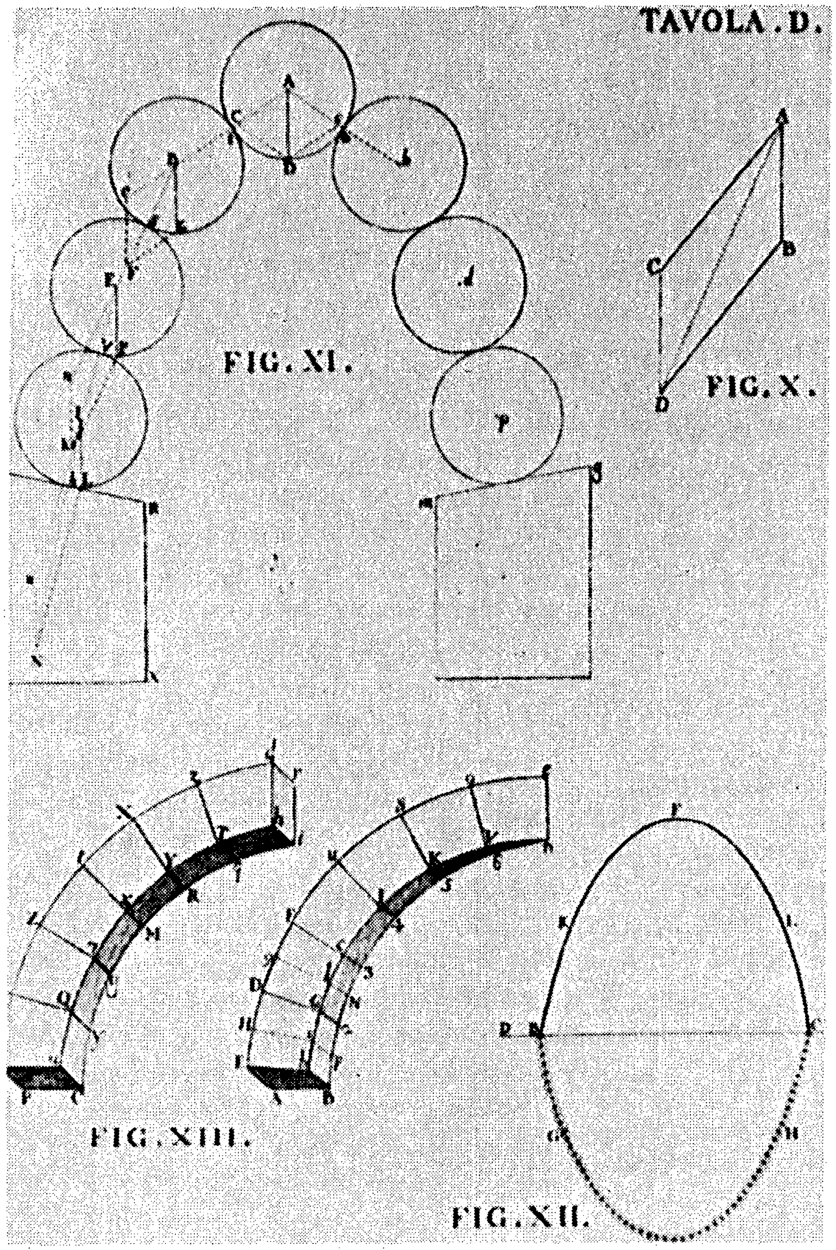


Plate in Poleni's *Memorie Istoriche* illustrating the catenary hypothesis.

authors. Of particular interest are his deliberations concerning the ideas of the mathematicians Le Seur, Jacquier, and Boscowitch.[25] These authors had applied a geometrical hypothesis to the problem of determining the lateral thrusts of the dome of St. Peter's Basilica, thereby obtaining a very high value, which, according to Poleni, was obviously false. Poleni believed that since the dome had been created by Michelangelo without the aid of mechanics or mathematics, then it should be possible to solve its problems without these sciences.[26] While Poleni explained that he was fond of mathematics and agreed with the anonymous Venetian philosopher who said that they could be useful to architecture, he did not think that mathematics should have priority in the architect's decisions: "Although excellent in themselves," they should not be abused in their application.[27]

Poleni criticized the solution proposed by the three mathematicians because it was excessively theoretical. He attributed the problems of the structure to "internal" and "external" natural causes. These were the aspects that always tended to undermine the solidity of buildings, and they did not result from errors in design or a lack of structural analysis. Among the factors Poleni cited were the quality of materials, their defective manufacturing or inappropriate use in construction, heat, humidity, the differences in pressure caused by several forces acting simultaneously, wind, thunder, and earthquakes. Poleni was also interested in experiments on strength of materials. He mentioned Musschonbrek's *machina divulsoria* and reported the results of his own experiments on the resistance of steel. He referred to these results in his final recommendation: Use steel reinforcing rings to relieve the tensile stresses on St. Peter's dome; this will help to avoid any further deterioration.[28] In the end, Poleni had greater confidence in his own empirical observations than in any geometrical theory of statics. Wherever he referred to theories or even to his own quantitative results, his conclusions were modified by the experience contained in traditional practice.

As in the case of other technical subjects, the tension between a theory that could be transformed into an instrument for the domination of the physical world and a practice still justified in relation to a metaphysical framework was much more evident in eighteenth-century Italian texts. In his *Dialoghi sopra le Tre Arti del Disegno*, Giovani Bottari envisioned a debate between two knowledgeable personalities of the previous century: Pietro Bellori and Carlo Maratta.[29] Bellori affirmed that to design solid and stable buildings, the architect required much practice. Maratta replied that the study of particular cases was not sufficient since this was useless when circumstances changed. Maratta stressed the necessity of establishing universal rules that would guide the actions of young architects by teaching them how to measure the stresses in arches and vaults and the resistance of walls. He believed that such knowledge could only be gleaned from geometry and was to be found in treatises on mensuration, strength of materials, and mechanics. Bellori tried to refute this argument by emphasizing the virtues of the great monuments of the past, all of which were created without the use of geometrical hypotheses. The discussion was inconclusive, but it was perhaps significant that in the end, Maratta also praised the artistic achievements of the Renaissance and called for a new synthesis of the arts in the persons of universal men, equally able as painters, sculptors, and architects.

Ermenegildo Pini explored the same issue in his *Dell'Architettura, Dialogi* (1770), in which fictional students of mathematics discussed the difficulties involved in applying geometrical theories to architecture and construction. The first student propounded the need to know rules in order to determine thrusts and structural stresses (rules derived from "the universal mathematics of Newton," the theories of Leibniz, and the calculations of Bernoulli).[30] But he admitted there were great difficulties involved in the application of these rules to practice due to the irregularities of vaults and the diversity of forces acting upon them. A second student added that the greatest architects had never applied mechanics to their buildings. In his opinion, it was more important to have relevant knowledge of the quality of materials; algebraic equations and the subtleties of theoretical mechanics and calculus were unable to ensure the stability of buildings. His conclusion was, surprisingly, that architects should design simple buildings so that they could be easily understood and analyzed by means of the geometrical rules of statics. Such buildings would be not only structurally sound but also beautiful "according to the law of continuity in nature." Such an assertion, alluding to Newton's universal empiricism, obviously brings to mind the projects of late Neoclassical architecture in France and clearly points at the ambiguous role of geometry and number in eighteenth-century architectural theory and design.

Francesco Ricatti wrote about "the science of proportions" in his *Dissertazione intorno l'Architettura Civile* of 1761. As a liberal art, architecture should, in his opinion, possess true and positive rules, capable of guaranteeing the solidity and stability of buildings without offending their proportions and beauty.[31] Ricatti stressed that architects should use optics for their projections, geometry to combine in one structure arches of different dimensions, and "music together with analysis" (!) to solve the problem of the harmonic mean, thereby producing a stable and universal law.

This same "confusion" appeared in Nicola Carletti's work. Influenced by Christian Wolff, Carletti postulated an architectural theory *more geometrico* and devoted a chapter of his *Istituzioni d'Architettura Civile* (1772) to the traditional notions about proportion and the determination of the dimensions of piers "taking into account" the strength of materials.[32] After enumerating the different types of columns, walls, and piers used in architecture, he described his "experiences" with statics, mentioning the weight of materials and a rule for determining the thickness of walls. But then Carletti immediately returned to the traditional notion of the human body as a prototype of proportion, stating that this "postulate" could be demonstrated through "experiments." The ambiguity created by the simultaneous presence of a geometry with symbolic resonances and the mathematics of technology is even more evident in the final scholium, where Carletti (repeating an assertion by Wolff) declares that if the rules of statics or geometry did not coincide with the "institutions of architecture," then experience should have priority over reason.

In his eclectic *Principi di Architettura Civile* (1781), Francesco Milizia maintained that proportions were of fundamental importance for architecture, but that no one had as yet found satisfying rules. Referring to previous opinions by Frezier and Patte, he remarked that architectural proportions were not "arithmetic, geometric or harmonic," but were derived a posteriori from the observation of nature and were intimately related to the stability and solidity that they provided.[33] In the third part of his *Principi*, Milizia argued that architects had to know something of experimental physics and mathematics. It was essential for practice to bear in mind the precepts of theory in order to "reflect, observe, confront, and even experiment," thereby establishing certain rules and contributing to the progress of art.[34] Milizia displayed a thorough knowledge of the works of French architects and geometricians and included in his book tables, rules, and experimental results. He cited the works of Musschonbrek, Bélidor, De la Hire, Frezier, and Camus, among others. However, he also thought there were limitations involved in the application of statics to construction, and in the end, if he thought geometry and mathematics were indispensable to architecture, it was because he also recognized their importance as symbols. Milizia stressed that above and beyond its technical applications, geometry was necessary "to understand correctly the important doctrine of proportions."[35] Thus, like their predecessors, eighteenth-century architects held, however incoherently, that geometry and numerical proportion endorsed the relation between aesthetic values and solidity, stability, and durability.

The *Rigoristti*: Structural Function as Metaphor

The most original Italian interpretation of this paradigmatic problem of Neoclassical architecture is to be found among the *Rigoristti*, the disciples of Carlo Lodoli, the Venetian "Socrates of architecture." Historians who have studied Lodoli's devastating criticism of Vitruvian authority and the classical orders have called him a true "modern." Recently, however, this perception has been qualified.[36] In many respects, Lodoli's understanding of architecture and history appears to be more profound than even that of most nineteenth- and twentieth-century theoreticians. This was probably due to his friendship with Giambattista Vico, the exceptional Neapolitan philosopher whose work anticipated certain insights of contemporary phenomenological hermeneutics.

Lodoli's writings have not survived, and like Socrates's teachings, his thought had to be set down by his students. In the first chapter of the *Elementi di Architettura Lodoliana* (1786), the most reliable of extant sources published after Lodoli's death, Andrea Memmo felt the need to justify the importance of Lodoli's theory, reminding the reader of the frequent failure of buildings due to structural unsoundness—failure that involved economic catastrophe.[37] A large part of this unusual treatise consisted of chapters on historical criticism in which Memmo discussed in the same enlightened mood Greek and Roman architecture, the theories of Vitruvius, and Renaissance and modern authors. Memmo then ventured a conclusion supported by his historical research: Although Vitruvius had defined architecture as a science, this art still lacked fixed and immutable principles. It was not even necessary to discuss this point. It was sufficient to recognize the great diversity of existing ideas about the essence of architecture to be convinced that "we are still in darkness." And since the most famous authors did not share one single clear idea, "we should at least have the courage to doubt."[38]

The fundamental criticism by the *Rigoristti* of all previous theories had already appeared in Francesco Algarotti's *Saggio sull'Architettura* (1753).[39] The argument was based on the notion that architecture should be consistent with the essence or nature of the materials used in building. Nothing could be more absurd than to use a certain material to *represent* another. Algarotti affirmed that falsehood was the greatest abuse of all. Architectural forms should therefore be compatible with the individual qualities of their materials, their rigidity, flexibility, or "resisting strengths." The "original" mistake of classical architecture, unconditionally accepted by modern imitators, was in fact the transposition of primitive wooden forms into stone or marble. Memmo emphasized that this diversity in materials, regardless of their various specific properties, made it impossible to establish definitive and absolute rules of proportion.[40]

Memmo pointed out that only two Italian authors, Milizia and Lamberti, had written about the problem of solidity and stability of buildings.[41] Lodoli, in his opinion, would have considered a knowledge of statics, strength of materials, and construction as essential for architecture. Vitruvius and other authors had written in the past *de re aedificatoria*, but had not thought to quantify the strength of materials or to calculate loads and stresses.[42] After demonstrating his familiarity with works on these subjects by the best-known French architects and geometricians, Memmo tells us that Lodoli himself had spent much time and effort in the elaboration of tables that summarized the results of his own experiments on the strength of wood, stone, marble, and other materials.

Also, Memmo refuted the validity of harmonic proportion, criticized the writings of Vitruvius on this subject, and showed how the Greeks themselves had not respected the original dimensions of the orders. These dimensions, he claimed, did not derive from a "beautiful nature," the human body, "which is unalterable," or the trees, as some others had suggested, but were the products of custom and a blind belief in the authority of the ancients. Memmo concluded by stressing that Vitruvius and his followers had been incapable of establishing a correct theory of proportions because they had disregarded the differences among building materials, particularly in relation to their "greater or lesser internal cohesion."[43]

Unlike most French architects of the Enlightenment, Memmo was capable of questioning not only Vitruvianism but *also* the myth of a transcendental nature. Nonetheless, we should not forget that the experiments on strength of materials and the ideas about the geometrical behavior of matter were not, for the *Rigoristti*, simple instruments of technology. On the contrary, these concerns were integrated into their interest in discovering the phenomenic essence of building materials. The new architecture was to be visibly true and was to represent the intrinsic properties of matter through the formal configuration of buildings. This is precisely the meaning of Lodoli's own work in San Francesco della Vigna; it is best illustrated by the famous windows with lintels shaped like catenary curves and by the "corollaries" that synthesized his teaching (which have been interpreted, paradoxically, as an early formulation of nineteenth- and twentieth-century functionalism).[44] Even Lodoli's contemporaries, including Algarotti, misinterpreted his thought as an absolute rejection of all ornament in architecture.[45]

Memmo wrote, "the straight function and representation are the two final scientific objectives of civil architecture."[46] These objectives he thought were equivalent: "Solidity, analogy and commodity are the essential properties of representation. . . . Ornament is not essential." The new vision of history that the *Rigoristti* shared with Vico enabled them to apprehend the synthetic and irreducible character of architectural value. In Vico's thought, history was postulated as the true science of man, a "new science," qualitatively different from natural science and capable of elucidating the origins of humanity.[47] The Vitruvian *firmitas, commoditas,* and *venustas* could not be conceived as independent, reified abstractions. Making use of historical criticism, Memmo could then question the traditional Vitruvian myths, but only to reveal the absolute primacy of man's original mythical structure. This phenomenological a priori, which embraced the idea of the "invariable body," had to be reflected in architecture in order to produce a truly meaningful human world. Meaning also became an explicit problem for the *Rigoristti*, as it was for the late-eighteenth-century French theoreticians. But Vico had emphasized that the humanity of man depended on his poetic being. Primitive man first dwelled in the world by implementing his poetic powers; he was initially a poet, not a scientist. And a fundamental form of *poesis* was, originally, building.

Hence, Memmo argued that although architectural value should derive from an appropriate use of materials, taking into consideration both their intrinsic properties or essences (precisely represented by mathematics and geometry) and the singular architectural program, the relations between form and matter had to be metaphoric and imaginative, not merely rational. This is far indeed from nineteenth-century structural determinism or the reductionistic obsessions of functionalism. Function, for the *Rigoristti*, retained the ambiguous dual connotation of abstract mathematics (number) and visible representation (quality). It could therefore be a symbol of human order. Memmo himself wrote that representation was "the individual and total expression that resulted when matter had been disposed with geometrical-arithmetical-optical reason;" this was done in order to fulfill a given architectural objective.

It should be remembered that ornament had never been perceived as superfluous by Renaissance or Baroque architects.[48] Regardless of theoretical discussions about the specificity of structure and ornament, the latter was always perceived as an integral part of a building's *meaning*. The problem of reconciling disjointed structure and ornament became explicit after the epistemological transformation of the late seventeenth century and was reflected in Perrault's work, the advent of Rococo, and by the autonomy of the technical dimension. Lodoli's attempt to reconcile ornament and structure in his "corollary" was already *beyond* Alberti's initial distinction, which had obviously relied on the traditional belief in the absolute value of the classical orders.

Inspired by Vico's understanding of history as the archetypal human science, Lodoli could produce his early criticism of Vitruvian theory, while simultaneously postulating the necessity of a symbolic intentionality in architecture. Perceiving the meaning of architecture as primaeval ritual building, a privileged form of reconciliation between man and external reality, he rejected the use of the classical orders because they were unsuited to masonry construction. Architecture as building had to respond to the poetic potential of the materials. This amounted to a rejection of a rational theory of architecture based on the models of natural science and mathematical logic, such as was prevalent in Europe during the eighteenth century. Like Vico, Lodoli rejected rational reductionism and put forward an early form of hermeneutic criticism as the most appropriate method for architectural theory. He could thus understand what Renaissance architecture had "lost" through the inception of theory and the division between design and building. The architect's fundamental role was to make poetry, not designs. Lodoli's theory was obviously overwhelmed by the new processes of production after the Industrial Revolution, and his profound criticism remained misunderstood by practitioners who took it to be simply a rejection of ornament. His reconciliation of ornament and structure is indeed so advanced that it is still an adequate criticism of simplistic "postmodernism."

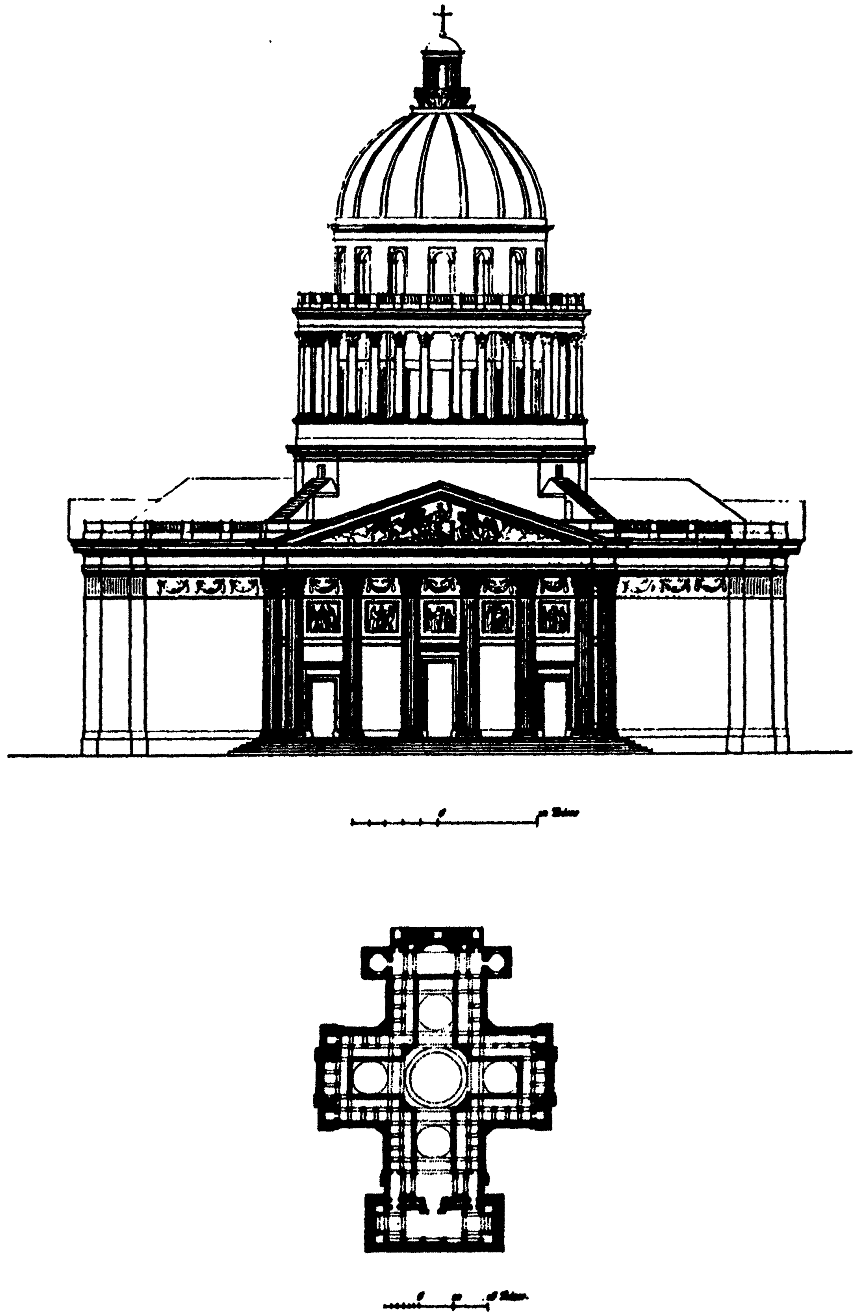
Perhaps the only architect to understand fully the sense of Lodoli's theory was Giovanni Battista Piranesi. Recognizing the limitations of *disegno* once it involved the reduction of building through the implementation of structural analysis and systematization, Piranesi became aware of the increasing meaninglessness of conventional architectural practice. Piranesi's architecture, for the first time in history, is fully embodied in his drawings and "visions" (and not in his very limited practice). His depictions of ruins and of a mythical Roman past are desperate attempts to reveal the meaning of an architecture that could no longer be built. This concern with meaning is, of course, parallel to that already examined in connection with late-eighteenth-century French architects, resulting in theoretical projects attempting to recover the meaning in the world. Piranesi's passionate interest in construction and his preference for the Roman "builders" over the Greek "designers" is, therefore, coherent with his other concerns. The Romans seemed to understand the poetic properties of stone, instead of merely translating, like the Greeks, the idealized forms of wooden temples. Piranesi believed that Roman architecture, deriving from the Egyptian and the Etruscan, was closer to mythical building, in the sense of the *Rigoristti.* But it was not enough to reproduce Roman buildings. Piranesi's "Roman" architecture was immense and overwhelming, often buried, mysterious, and prone to decay. Meaning could not be attained through conventional classical buildings or the implementation of a geometry that imitated nature; the drawing or engraving was the embodiment of the symbolic intention. Geometry or conventional forms would obviously be devalued if the represented buildings were placed in the context of the industrial world, in a city that denied the symbolic, intersubjective dimension of architecture.

In the famous *Carceri* etchings, Piranesi tried to understand the phenomenic essences of stone and wood architecture. This essential architecture occurs in a space that is already beyond perspective reductionism. Piranesi dominated the methods of perspective representation and the *scena per angolo* of the Galli-Bibienas. But his *Carceri* etchings are not illusionistic in a Baroque sense. He was not interested in producing the image of a building whose reality would be realized beyond the drawing itself. If the city had become a prosaic stage in perspective, and perspective was identified with reality, he used geometrical methods to create an intentionally ambiguous reality, an architecture where man would be confronted with the absurdity of his own powers of abstraction. His *Carceri* are an anticipation of cubism and surrealism; through the appearance of perspective they deny perspective reductionism and confirm the primacy of embodied perception. But all this is achieved not in the usual way, through a three-dimensional building, but through the reality of the drawing itself. The drawing is no longer the symbol of an intention that would be fulfilled in the surreality of the building, as in Baroque architecture; but the drawing itself becomes an architecture of geometrical essences, consciously avoiding the external world where mathematics was being transformed into a tool of technology.

Soufflot, Patte, and the Piers of Ste.-Geneviève

The most significant discussion concerning the application of statics to a building project occurred in Paris between Jacques-Germain Soufflot and Pierre Patte during the second half of the eighteenth century. The debate concerned the dimensions of the piers supporting Ste.-Geneviève's dome and clearly reveals the tensions and ambiguities that marked the architecture of the Enlightenment. Belief in the empirical method as the only access to truth encouraged the accumulation of a sufficient quantity of data eventually to transform the geometrical theories of statics into an effective structural analysis. Yet this same empiricism was also responsible for those architectural positions that appear traditional in comparison to the intentions expressed in theoretical and scientific texts during the first half of the eighteenth century.

I have shown how Patte, by adopting an empirical method in relation to the problem of the classical orders and their proportions, rejected the relativism of values attributed to Perrault's theory. In 1770 he published a *Mémoire sur la Construction de la Coupole Projectée de . . . Sainte-Geneviève* in which he argued that the dimensions proposed by Soufflot for the piers were not adequate to support the great weight of the dome.[49] Clearly, both architects were very interested in technical problems. Soufflot kept up with advances in geology and with experimental physics and chemistry and was himself involved in industry. And Patte believed that "the most important aspects of architecture (aside from the classical



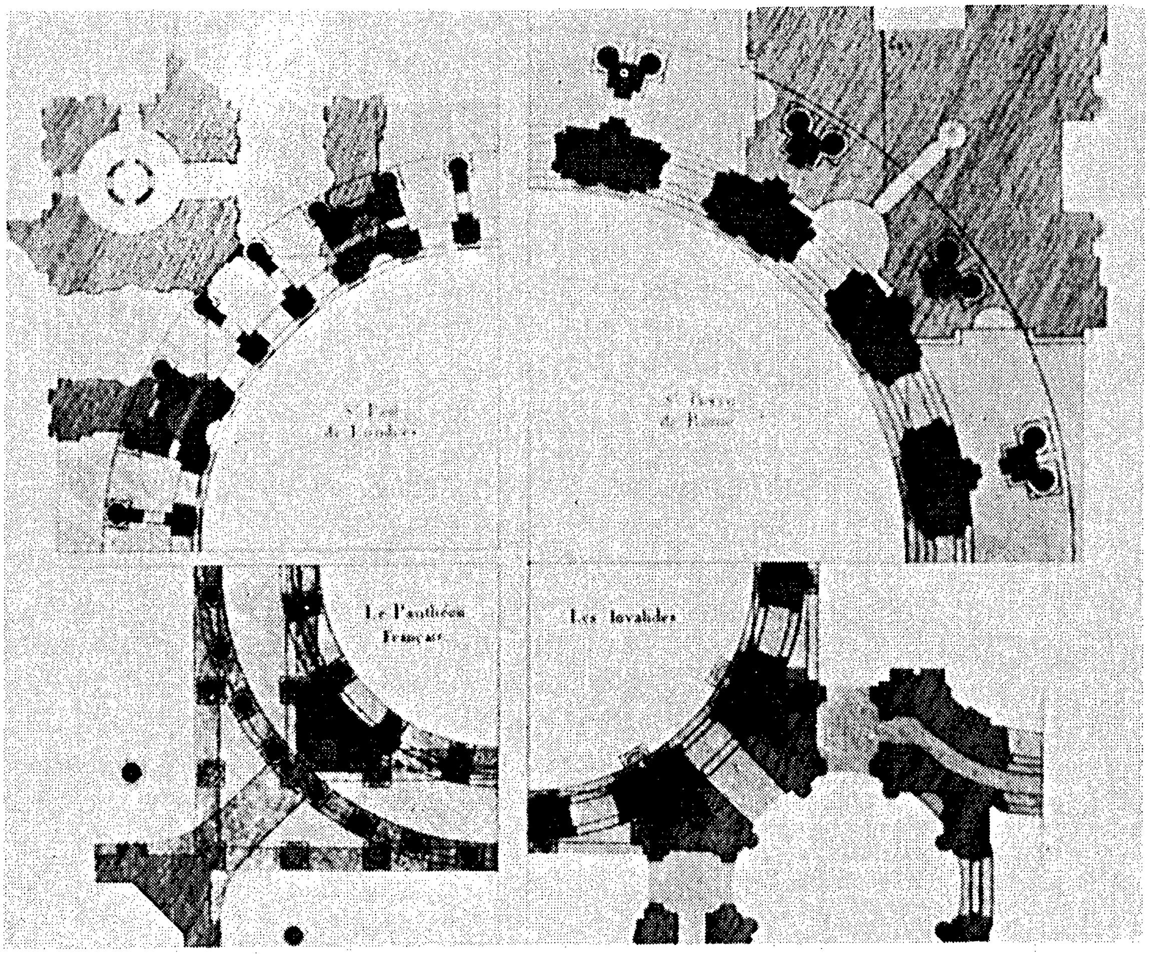
J. G. Soufflot's Ste.-Geneviève. Schematic plan and elevation showing the large mass of the dome and drum in relation to the rest of the building, from Quatremère de Quincy's *Histoire de la Vie et des Ouvrages* (1830).

orders) were technical problems of construction such as determining cubic volumes, cost estimates and specifications, and the building of sound foundations or entablatures reinforced with iron rods."[50]

Both men were aware of their predecessors' work in the field of statics and strength of materials. Patte's *Mémoires* mention Bullet, Frezier, De la Hire, and Bélidor, and Patte was actually the author of the two last volumes of J. F. Blondel's *Cours*, which dealt with technical problems.[51] The proportions he recommended for the classical orders were to be derived not from optical considerations, but from a determination of the loads they had to support.[52] Like Soufflot, he admired the lightness of Gothic structures,[53] and thus praised the synthesis of that quality with the nobility of trabeated classical architecture that characterized Ste.-Geneviève and Contant's project for La Madelaine.[54] The aesthetic norms of both architects were ultimately determined by a belief in an intersubjective taste and the power of numerical proportion to ensure positive beauty.

The differences between Patte and Soufflot should, therefore, be examined carefully. It has been pointed out that Patte represented a traditional and empirical approach to the problem of statics, while Soufflot and his supporters (Perronet, Rondelet, Bossut, and Gauthey) tried to implement a true theory of structures based on experiment and calculation. Although this view is not altogether false, it should be qualified. In his *Mémoire,* Patte invoked the aid of mathematics and mechanics, which in his opinion were indispensable to the progress of science. But after citing the works of Parent, Couplet, and De la Hire, he decided that the strictly geometrical rules proposed by Carlo Fontana in his *Tempio Vaticano* (1694) were the best means for determining the proportions of domes. In fact, what Patte could not accept was Soufflot's belief in the absolute infallibility of mathematical formulas and quantitative data derived from tests on the resistance of building materials to fracture. Instead, Patte thought that design decisions should correspond to the experience of everyday practice. He compared the dimensions proposed by Soufflot with those used under similar conditions by the great architects of the past: for St. Peter at the Vatican, St. Paul in London, and the churches of La Sorbonne, Les Invalides and Val-de-Grace in Paris. From this he concluded that the piers of Ste.-Geneviève were too slender and, if built as designed, would fail due to the load of the dome.

Patte might be called traditional because of his adoption of Fontana's simple geometrical rules, which lacked a mechanical



Comparison of the dimensions of the piers supporting large domed structures in Europe with those of Ste.-Geneviève, after Patte's *Mémoire* (1770).

or physical foundation and whose validity, he believed, was endorsed by the survival of ancient masterworks. On the other hand, Patte was conscious of the limitations on the applicability of mathematics and geometry to physical problems—limitations that Soufflot tended to overlook. In contrast with the ideas of Frezier or Bélidor, Patte emphasized the importance of practice in solving problems of structural mechanics. In volume six of J. F. Blondel's *Cours,* Patte affirmed that practice had always preceded theory and that the art of construction had in fact made great progress before the intervention of theory; admirable buildings had been constructed through simple routines and experience, not only during "centuries of ignorance" but also in his own time, when craftsmen executed difficult works based only on comparisons with similar buildings of the past.[55]

Unlike many of his contemporaries, who were obsessed with the potential of structural analysis, Patte was not surprised by the success of traditional buildings, which had been erected without the aid of mechanical theories. Construction, after all, was simply the art of elevating bodies over other bodies, fashioning their verticality and position by means of diverse combinations and relations based on a small number of rules of statics—rules that were part of everyday experience and thus an extension of common sense. For example, the weak must be supported by the strong, and a slope is essential for the stability of piled objects. Deceptively simple, such knowledge had to be gleaned from experience and practice. Only in his way could the architect determine the appropriate dimensions of his structures without endangering their stability while also avoiding a wasteful use of materials.[56]

The great success of historical monuments demonstrated, according to Patte, that the rules established through routine and practice should not be ignored. He did not object to architects' and geometricians' recent applications of a mechanical theory to construction since, he felt, this amounted to substituting routine with fixed principles founded on the development of the "eternal laws of weight and equilibrium."[57] He believed that the discovery of these absolute geometrical laws was important, but he stressed that such laws should always be able to take into account the real problems of practice. Scientists often encountered insurmountable obstacles when dealing only with simple problems of the thrust of vaults, and due to their lack of practical knowledge, for which there was no substitute,[58] they could only contribute minimally to the advancement of construction. This state of affairs had precipitated, in Patte's opinion, "the invention of principles and hypotheses" not in accordance with the facts: "In a word, only the reunion of practice and theory can allow for a profound treatment of the subjects concerning construction."[59]

The synthesis of theory and practice was obviously not equivalent to a simple rejection of statics by a conservative practitioner. Patte was familiar with the empirical methods of science and recognized their potential to provide fixed quantitative results through experimentation. In his *Mémoires*, he cited Buffon's tests on the resistance of steel,[60] and in the *Cours*, he emphasized that the precise knowledge of the loads that different types of stones could support was very useful.[61] He also complained that architects often determined the dimensions of their buildings only through approximation and not through the application of the laws of equilibrium.[62] He distinguished between De la Hire's mechanical hypothesis about the thrust of vaults (which he praised) and seventeenth-century rules of a merely geometrical character. In fact, he believed that De la Hire and Frezier represented the culmination of the possible applications of mathematics to construction: "The limits of this art seem to have been fixed because educated people are now capable of appreciating and calculating in advance that which can or cannot be executed; there are no more enigmas in this respect but for the ignorant."[63]

It is likely, then, that Patte's criticism of the project for Ste.-Geneviève was motivated by conflicting considerations, which were reconciled only in the eighteenth century. On the one hand, guided by the strict rationality of empirical science, Patte revealed the distance that still existed between the geometrical theories of statics and the real problems of practice. On the other hand, he retained a traditional understanding of architectural value, which was legitimized by the metaphysical dimension implicit in his empirical method. Thus he believed, like Soufflot, that the same mathematical rules provided for stability and beauty. But these rules were derived, in Patte's case, from *both* empirical observation and historical precedents, that is, from the totality of the architect's personal experience, which he felt had priority over ideal calculations as the origin of meaningful design.

The polemic continued for thirty years. In time the piers of Ste.-Geneviève failed due to the normal deficiencies of building procedures, which Soufflot had disregarded in basing his calculations only on the experimental resistance of the stone. The alarming cracks in the piers kept the discussion alive long after Soufflot's death, and in 1798 Patte was still writing critical *mémoires* on the subject.[64]

Emiland Gauthey, a brilliant *architect et ingénieur des ponts et chaussées*, took it upon himself to defend Soufflot. His name has been mentioned as the author of a text incorporating Laugier's theory and as the inventor of a machine to test the strength of stone. In 1771 he published a paper accusing Patte of having mistakenly used De la Hire's hypothesis of frictionless voussoirs in his calculations while ignoring the adhesive force of mortar.[65] Patte admitted in one of his letters that some of his calculations were indeed based on the theory that Soufflot had used, but that his own results were always tested by practice and historical precedents.[66] Gauthey criticized Patte's reverence for old monuments, his approval of Frezier's theory, and especially his adoption of Fontana's principles. In the end, Gauthey also applied De la Hire's hypothesis to the problem, but his conclusion was just the opposite of Patte's; in his opinion, the piers projected by Soufflot could support an even larger and heavier dome.[67]

Gauthey shared Soufflot's faith in the possibility of applying geometrical hypotheses to the resolution of practical problems of construction. It is perhaps significant that Charles-François Viel, an early-nineteenth-century architect and critic (of whom more will be said later) blamed Gauthey and Bossut for causing Soufflot to abandon the rules of traditional building, which were still observed by most of his contemporaries. Such disregard had brought about, in Viel's opinion, ominous consequences for architecture as a whole.[68]

Throughout the eighteenth century, architects, engineers, and geometricans, impatient to see Galileo's dream come true, applied the theory of statics to certain specific structural problems. Some, like Patte, were more cautious and recognized the limitations of such applications vis-à-vis traditional building methods. But while they shared the same curiosity and passion for technical problems, their enthusiasm was modulated by the implications of the empirical method. Furthermore, the residual symbolic character of numbers and geometric figures impeded the application of infinitesimal calculus to the realm of human action. The survival of Euclidean geometry constituted the most fundamental obstacle to the establishment of a universal theory; its unchallenged presence as the only form of geometrical science served to stall the final reduction of building operations into a generalized technological process until the end of the century.

After 1770, however, several scientists and engineers—for example, Prony and Carnot, future professors at the *École Polytechnique*, and Bossut and Coulomb, from the *École du Génie*—began to perceive the need to revise the old theories of statics.[69] The eighteenth century had produced two types of scientists: those who, like Musschonbrek and Buffon, were mainly interested in experimental physics, and others, like Euler, whose interest in geometry and applied mechanics was frequently motivated by hidden metaphysical concerns, so that their scientific involvement was merely to demonstrate the power of mathematics. In spite of architects' and engineers' wish to join theory and practice in technical problems, the definitive mathematization of the principal factors of physical reality, the mathematization of sufficient precision to provide analytical solutions of structural problems, did not come about until 1773, when Charles-Auguste Coulomb presented to the Royal Academy of Science his paper "On the Application of the Rules of Maximums and Minimums to Some Problems of Statics Relative to Architecture."[70]

Following a successful career as a military engineer, Coulomb studied at Mezières and then turned to science. He proposed a method of algebraic analysis that allowed for the consideration of the effects of friction and cohesion in structural problems, the two fundamental aspects that had either been ignored in previous theories or merely observed experimentally. Coulomb was the first to propose a truly scientific method for solving structural problems, effectively taking into account essential practical requirements. In the first part of his work, he provided a full discussion of the original problem of Galilean mechanics: the forces acting upon a typical cross section of a cantilever beam. In the second part, he examined the two most popular structural problems of the eighteenth century. Unhappy with the theories about retaining walls that appeared in books by Bullet and Bélidor, and which were based on a strictly geometrical conception of statics, Coulomb was finally in a position to reduce the physical properties of the retained earth and of the wall's masonry to the conceptual level of mathematics. His equation for the design of retaining walls is still useful today.

With regard to the problem of stability of arches and vaults, Coulomb overcame the difficulties that had impeded the effective application of De la Hire's theory to practice. His method of analysis took in the quantitative values of friction and cohesion as well as the fact that fracture did not always occur at the crown.

As Poncelet wrote in 1852, "Concerning the equilibrium of arches, before Coulomb, one possessed only mathematical considerations or very imperfect empirical rules based on limited hypotheses, the majority lacking that character of precision and certainty that alone can recommend them to the confidence of enlightened engineers."[71]

Coulomb's paper was not presented in a way that allowed for an easy application of his discoveries to architectural and engineering practice. This would still take a few decades. Nonetheless, it is significant that in the first history of statics ever written, an introductory chapter to P. S. Girard's *Traité Analytique de la Resistance des Solides* (1798), Coulomb's theory was referred to as the culmination of a development that had started with Galileo.[72] Girard thought that Coulomb's contributions constituted a true *fil d'Ariadne*, guiding practitioners through the labyrinth to truth. Girard used Coulomb's discoveries as the premise of his own work, producing the first truly analytic treatise on the science of strength of materials as we know it.

Girard explained that although motion in the theory of statics could be conceived in terms of absolutely rigid levers, this supposition was inadmissible when statics was applied to the calculation of real machines or construction. Nature had not created substances whose parts might not be severed. There were, therefore, two types of equilibrium: one is between two opposing forces in balance (for example, a lever), the other is between a certain function of these forces and the internal cohesion of the constituent parts. The conditions of the first kind of equilibrium could be determined rigorously, but those of the second only approximately.[73] Girard quoted d'Alembert's remark that experience should be used not only to prove a theoretical insight but to provide new truths that theory alone would be incapable of discovering.

Girard's work represented the first successful integration of experimental observations on the strength of materials into the mathematical structure of theory. Experimental data, which normally referred to fracture loads, had been considered in a more or less arbitrary fashion and never became, during the eighteenth century, a true vehicle for reconciling geometrical hypotheses with empirical reality. In Girard's *Traité*, quantitative observations became mathematical coefficients. His theory is truly *analytical*, avoiding the use of Euclidean geometry. Finally, architectural reality could be truly functionalized, allowing for an effective substitution of mathematical rules for the experience derived from building practice. Building practice could now be effectively controlled and dominated by "theory." The *Institut National*, founded after the Revolution, "solemnly" adopted the conclusions of Girard's work in a report signed by Coulomb and Prony.

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GEOMETRY, NUMBER, AND TECHNOLOGY