LEONARDO DA VINCI: ENGINEER AND ARCHITECT (MONTREAL: MONTREAL MUSEUM OF FINE ARTS, 1987)

I.1

The Career of a Technologist

by
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From myth to historical reconstruction

The enormous body of literature on Leonardo still betrays a striking hesitancy to present a precise definition of his personality: artist, architect, inventor, philosopher, scientist. For a long time, the vastness of Leonardo's interests led to the view of him as the very incarnation of genius, a genius who ignored the boundaries of the various disciplines and roamed freely through the immense realms of knowledge. Since the end of the last century, when Leonardo studies began to follow the hard and fast guidelines of historical and documentary rigour, it has not often happened that scholars have seriously focused their attention on Leonardo's activity as an engineer. They have preferred to linger over his extraordinary talents as a painter and architect, or to insist upon his impressive gifts as a scientist. And yet careful study of the highly revealing body of the Leonardo papers and manuscripts that have come down to us makes it difficult to escape the impression that, in fact, most of his energy was devoted to activities of a technological nature.

The story of Leonardo's eventful life, which still contains many uncertainties, clearly indicates that the money which Leonardo, who had no independent income, was able to earn (and which enabled him to have a fairly comfortable lifestyle) came largely from his work as an engineer in the service of various patrons. Indeed, the money he earned from his activity as a painter was merely an additional source of income to his practically constant earnings as an engineer.[1*]

Leonardo was an engineer in the sense that the expression had in his day: an inventor and builder of *ingegni* (complex machines as well as simple mechanical devices) of every sort and for every type of operation. The figure of the engineer, along with that of the *condottiere* or military leader, typifies Renaissance court life. It was within the context of the court that the engineer carried out his many duties, first and foremost of a military nature. He was expected to furnish technical solutions for making offensive weapons more effective and systems of defence more solid, to provide an army on

*The notes of chapter I.1 are on page 317.

the move with transportation on functional wheels or temporary bridges for crossing water courses that would be both sturdy and rapidly constructable. He was required moreover to modify the course of rivers in order to isolate an enemy under siege or, perhaps, to flood cities or fortifications. But Renaissance lords, particularly the great ones, had other needs besides military ones. They had agricultural and industrial interests and their profits could be greatly increased by the introduction of the mechanization of methods of irrigation or production. The Renaissance lord beautified cities not only with magnificent buildings which reflected the image of his own power, but also with large-scale public works, especially of a hydraulic nature (acqueducts, canalization projects, etc.) for the benefit of the general public. Finally, he maintained a sumptuous court, which often provided the setting for festivals and performances intended to create a sensation in keeping with his reputation. And it was not by chance that the organization of such performances — but also the invention of mechanical marvels for parks and gardens — offered the great engineers of the Renaissance extraordinary opportunities to display their talent.[2]

This is the vast horizon that characterized the activity of the Renaissance architect-engineer, at least at the beginning of the fifteenth century and, above all, on the Italian scene. The professional profile of this group of individuals was substantially homogeneous. From Taccola[3] to Brunelleschi,[4] from Francesco di Giorgio[5] to Leonardo, the tasks and functions of the court engineer were essentially the same. The backgrounds of these architect-engineers also have strikingly similar characteristics. They were all men of humble origin who had learned their profession in that great school of practical applications that was the Renaissance workshop. None of them had pursued a regular curriculum of studies, nor did any of them spend his entire career in the service of a single patron. They preferred the Italian language to Latin; they wrote little or not at all (Brunelleschi) and, with the partial exception of Francesco di Giorgio who attempted to write a comprehensive treatise,[6] their writings were of a fragmentary nature, essentially collections of drawings accompanied by brief captions in which they frequently made use of cryptographic systems to protect an invention from indiscreet eyes. In addition to their technical duties, especially on a military level and in the field of hydraulics, they were all practising architects, and some of them were successful painters and sculptors (Francesco di Giorgio). Their scientific background was as limited as their readings were modest. They all toiled to decipher Vitruvius, turning to various humanists for assistance.[7] They were familiar with a few principles of mediaeval statics[8] (but stripped of the quantitative analysis that characterizes those texts), practical arithmetic and, in the best cases, some rudiments of Euclid. The basic nucleus of their expertise was the fruit of jealously guarded methods learned either by experience or in the workshops of the masters to whom they had been apprenticed. These engineer-architects were greatly in demand, and not only by the Italian lords. Taccola served King Sigismund; Brunelleschi received important commissions from the Florentine authorities; Francesco di Giorgio offered his services to many Italian lords, finding his chief patron in Federico da Montefeltro of Urbino. Well paid, respected, admitted directly into the presence of princes, during the Quattrocento the most qualified of these engineers enjoyed a fine reputation. At a time of great change, of continual wars which saw the emergence of an entirely new military technology (firearms), of technically daring, immense buildings (Florence Cathedral), of rapid development in commerce and production (particularly in the fields of metallurgy and textiles), the services of these men were of fundamental importance.[9]

During those decades of great change and expansion, faith in the extraordinary possibilities of increasing wealth and well-being and of improving the quality of life through the use of new technologies grew continually until it became a veritable utopia to which not even the engineers who were to make it a reality were immune. Hence it is not surprising that in this atmosphere their role in society became increasingly important.

Until a few decades ago, no one would have been willing to approach the problem of Leonardo as an engineer in terms of a career that developed within a professional tradition which others before him had inaugurated, a tradition based on specific knowledge and procedures. Today, fortunately, the traditional tendency to isolate Leonardo from the context in which he operated is dying out, and scholars are redoubling their efforts to place him within the framework of his time. Thus it is becoming evident that Leonardo's activity as an engineer followed the pattern and code of behaviour of a profession which was already firmly established. It is also obvious that one cannot properly or profitably talk about Leonardo as an engineer without taking into account the activity of the illustrious colleagues he imitated and whose abilities he sincerely admired. This does not mean that Leonardo's contributions in this field should be re-assessed, nor that he should be seen as simply having repeated techniques that had been conceived and put into practice by those who had preceded him. To take into consideration the network of relationships, of exchanges of professional experiences and knowledge that linked Leonardo to engineers of his own time and of earlier generations, does not make his activity in this field any less fascinating or original. Indeed, some recent scholarship, reacting against the long tradition of exaggerated celebration of Leonardo as a solitary genius, has tended to relegate his activity as an engineer to a sometimes clumsy imitation of his less famous colleagues. This is clearly an unacceptable conclusion.[10]. This complete reversal of historical perspective — from Leonardo seen in total isolation to his dissolution in his historical context — is probably an inevitable reaction. Like its exact opposite, this new historical perspective precludes the possibility of correctly assessing the significance of Leonardo's activity in this field.

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To arrive at a balanced evaluation of the significance of Leonardo's technological studies it is first necessary to deal with a fundamental and arduous critical problem. In essence, it is a question of finding the proper way of orienting oneself within the enormous, chaotic bulk of Leonardo's surviving papers. The slightly less than six thousand pages in Leonardo's hand that have come down to us correspond to about one third of the papers that Leonardo left as a legacy to his faithful pupil Francesco Melzi at the moment of his death at Amboise in 1519.[11] In spite of this heavy mutilation, these papers constitute the most extensive, detailed, and revealing documentation that we possess of the technology of the Renaissance. Without them, our knowledge would be drastically impoverished, not only with regard to technology during the fifteenth and sixteenth centuries in Italy (Florence, Milan, central Italy, and Rome, the centres where technology had advanced the most), but also with regard to other European countries, especially France and the already technologically advanced German-speaking nations.

Leonardo's manuscripts, in fact, do not contain precious information solely on his activities and his experiments. His manuscripts also present a confused but extremely rich picture of the entire panorama of the technology of his time. How then, in this tangle of notes and drawings, can we distinguish Leonardo's personal contributions from the ideas of others which had particularly struck him?

In rejecting the excesses of the celebratory type of scholarship that saw Leonardo as the sensational anticipator of every important modern device or machine (from the automobile to the airplane, from the steam engine to the submarine), several scholars called attention, in the last decades, to the fact that there are illustrations of several of Leonardo's sensational "inventions" in manuscripts and iconographical sources that unquestionably date from before him (see Pls VI-VII); thus the gradual reassessment of the long list of Leonardo's discoveries began. At the same time, criteria were devised for reading Leonardo's technological notes and drawings in a less "condescending" way than the one given since the early 1900s by those who began the popular practice of making working models based on Leonardo's drawings of machines and mechanisms. Using as their point of departure largely incomplete sketches of doubtful interpretation (the automobile and airplane are the most telling examples of this), these scholars did not hesitate to produce working models by integrating into Leonardo's drawings basic construction details which were not indicated by him.[12]

Fortunately, today a different attitude is gaining ground. Leonardo's drawings, and the captions where they occur, are accepted in the degree of completeness they actually possess. Thus the temptation to correct or complete them with the justification that this or that decisive detail had been intentionally omitted by Leonardo to protect his discovery is resisted. This more recent attitude toward Leonardo's technical studies has led to the discovery that a significant number of his designs (the case of his many studies for a flying machine is particularly illuminating) are not technically plausible, or are sometimes impossible. Thus a whole section of Leonardo's technological research is coming to be seen not so much as actual projects for devices that were to be immediately constructed, but rather as a sort of technological "dream", the product of a highly fertile imagination. Leonardo's manuscripts — but also those of other Renaissance engineers — are full of technological "dreams" of this kind, often described in minute detail. And yet it is difficult to imagine that Leonardo could have deluded himself that such devices were feasible. Leonardo's technological "dreams" are of a greater interest. They attest, in a man who was particularly versed in engineering, to a faith in the development — through technology — of unheard-of powers in man (to fly like a bird; to live underwater like a fish). Leonardo thus gave voice to the enthusiasm and quest for innovation of an entire age marked by sensational discoveries (suffice it to mention the invention of the printing press) and by the continual expansion of geographical horizons. It is not by chance that Leonardo's technological "dreams" often have a prophetic tone or are accompanied by reflections on human nature, as in some of his studies of flight or in the famous note in which he states that he wishes to keep secret his invention of a way to breathe underwater to prevent it from being used as an instrument of death.[13] Leonardo grasped that technology, along with its obvious potential benefits, could also bring considerable risks to humanity, thus anticipating the dramatic debate on the relationship between the advancement of technology and the degeneration of human nature which has raged throughout the history of modern culture and is more lively than ever today.

It should also be stressed that a considerable part of Leonardo's technological studies records the intense activity of an engineer who for the entire span of his long life was in the service of powerful patrons from whom he constantly received requests and specific commissions in exchange for a special fee or a regular salary. Leonardo designed, on his own initiative, technical solutions which he knew would be useful to his influential patrons, hoping to receive special rewards from their realization. This category includes practically the entire series of Leonardo's studies of military technology, the most noteworthy group of his investigations in the field of applied hydraulics, several large artistic projects involving complicated technical problems (such as the equestrian monuments for Francesco Sforza and Gian Giacomo Trivulzio,[14] with their extremely delicate casting problems), his spectacular designs for festivals and theatrical performances at court,[15] not to mention his numerous studies of particular technical problems that were often quite down-to-earth (such as the mechanism for providing hot water for the bath of the Duchess Isabella of Aragon[16]), which he was requested to solve by his powerful patrons. Also belonging to this group are many of Leonardo's technical studies aimed at the most efficient use of energy sources and the mechanization of certain systems of production which it is difficult to imagine Leonardo undertaking without being requested to do so by an interested patron.

This same group includes the largest part of Leonardo's technological studies, which are consistently characterized by an empirical approach similar in style and method to that of the engineers of his time. These specific studies never reveal an attempt to derive the technical solution adopted from general laws and principles. In order to single out the many studies that belong to this category, it is necessary to take into account the information provided by the reconstruction of Leonardo's intellectual and material life. The identity and requirements of his various patrons help us in tracing the origin of a growing number of Leonardo's projects. In fact, many aspects of his technological activity appear to be not so much the fruit of an autonomous, highly fertile inventive capacity, as the direct consequence of his presence at a certain time in a certain place, in the service of this or that lord.

Another considerable group of Leonardo's technological studies is of a different nature. These studies, which cannot be directly related to specific commissions from patrons, are a record of the evolution of an autonomous process of professional "retraining" for which, at a certain point, Leonardo felt the need. These are more comprehensive, less fragmentary studies and reflect Leonardo's attempt, increasingly intense after 1490, to establish a connection between general principles and specific applications, thus rooting technology in science. For Leonardo, studies such as these not only enriched and perfected the possibilities of technological projects, but also tended to confer a new significance upon the profession of the artist-engineer. To repeat the expression used by Leonardo himself, they tended to transform him into a perfect imitator of Nature. For Leonardo, in the field of technology as in painting, the imitation of Nature presupposed the full capacity to grasp the ironclad laws that govern every natural process; hence for him to invent meant nothing other than knowing how to reproduce. Leonardo's studies of this kind display a progressive attempt to compile a new encyclopaedia of knowledge. The confused fragments that remain are sufficient to illustrate the effort made by Leonardo as well as the boundless dimensions of his ambitions. It was an arduous undertaking for someone like Leonardo, who had never had a regular education and never fully overcame his uncertainties in Latin and geometry. He attempted to unravel the secrets of movement. His attention lingered, fascinated, over the element of water, "*vetturale di natura*" (Nature's carrier). He carefully observed the flight of birds, realizing the necessity of broadening his research to include the element of air and the nature of the winds. He devoted himself to extensive research in mechanics, recognizing movement, weight, force, and percussion as the four "powers" of Nature. He immersed himself in the study of physical geography and anatomy. Along with Leonardo's interest in problems of a general nature, and in the constant laws governing various phenomena, we continually find in these studies his concern with a new, ambitious approach to useful applications ("*giovamenti*"). As the historian of science, Alexandre Koyré, put it, in these studies Leonardo seems to be transformed from a "technician" into a "technologist".[17]

The schematic division of Leonardo's technological studies into the three categories outlined above (technological "dreams", specific commissions, and attempts at deriving applications from general laws) omits a certain number — not precisely definable, but certainly quite consistent — of technical projects belonging to a fourth distinct group. These studies include drawings and notes on machines and mechanical devices derived from the experiences of others. Included in this group are "quotations" from contemporary and earlier authors (including the "classics"), the recording of technical solutions which Leonardo had witnessed in the course of his many travels, and memoranda regarding operational methods or devices of which he had learned from technicians of his acquaintance or who worked under him. The "quotations" can be identified (although not always, nor easily), and today we possess a long list of texts which Leonardo used as precious sources (Vitruvius, Valturius, Francesco di Giorgio, and so on).[18] The identification of the studies which record solutions or devices that had particularly struck Leonardo or which had inspired him — as was often the case — to improve them, is considerably more difficult. In a few cases identification is made possible by a note written by Leonardo himself, but in general one can only make cautious conjectures in the hope that further studies on the culture and technical practices of his time and of the places in which he lived will provide us with more precise guidelines.

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The objective of introducing criteria of distinction into the mass of Leonardo's studies requires not only an intense, systematic effort of contextualization, i.e. of precise references to his sources, his assignments and his environment. It also presupposes an attempt to establish, at least roughly, a chronological sequence for his drawings and notes on technology. This requirement, indispensable in all areas of Leonardo studies, is of unique importance for understanding Leonardo the engineer and scientist.

In the bulk of Leonardo's surviving writings, in fact, the documentary nucleus of greatest size and importance is constituted by the monumental Codex Atlanticus. Inaccurately called a "codex", suggesting a coherence of which it is totally devoid, the Atlanticus consists of a collection of more than a thousand pages of various sizes in which contents of a technological and scientific nature clearly predominate. This "album" was put together at the end of the sixteenth century by the sculptor Pompeo Leoni,[19] who took apart the many Leonardo notebooks in his possession with the intent of distinguishing the documents of a technical-scientific nature from those that represented studies of an artistic nature (including anatomical studies). The latter were included by Leoni in a second compilation, corresponding to the present-day corpus of Leonardo's drawings at Windsor Castle.[20] The Codex Atlanticus groups together sheets dating from the entire span of Leonardo's career. These sheets come from original notebooks which are impossible to reconstruct and are arranged with no apparent thematic or chronological criterion. Leoni's attempt to organize Leonardo's papers was truly a disaster, to a great degree an irreversible one, and it has made the historian's task of critical reconstruction extremely arduous.

In spite of these difficulties, the necessity of attempting a reconstruction, if not of Leonardo's original dismembered notebooks then at least of the chronological sequence of the sheets contained in the Codex Atlanticus, has gradually come to assume a growing intensity in modern Leonardo studies. A landmark in this effort was Gerolamo Calvi's masterly volume,[21] published more than sixty years ago. Calvi, who had already published a model edition of the Codex Leicester (today Codex Hammer),[22] not only pointed out the need for a precise chronological ordering of Leonardo's works, but himself offered several masterly examples of this, establishing the chronological boundaries of the then known Leonardo manuscripts in terms which are still substantially accepted today. Naturally Calvi devoted special attention to the Codex Atlanticus. In fact, he provided an extremely useful series of indications which made it possible to assign fairly precise dates to a significant number of Leonardo's papers in the collection of the Ambrosiana Library. Calvi's work, which is still an unsurpassed model of Leonardo studies, was fortunately followed and imitated by other scholars, whose investigations of individual sheets or groups of sheets from the Codex Atlanticus have provided valuable chronological indications. In the last few decades, great progress has been made, due particularly to the comprehensive work initiated by Carlo Pedretti,[23] who also availed himself of the opportunity to conduct an orderly and systematic investigation of the Codex Atlanticus and the Windsor drawings.[24]

After his promising early work of thirty years ago,[25] in 1979 Pedretti published a complete catalogue of the Codex Atlanticus.[26] In this catalogue, sheet by sheet, he provides — on the basis of paleographic considerations, style of drawing and handwriting, as well as relationships with other datable sheets or known episodes in Leonardo's life — justifiable indications for the chronological situating of documents, to which he not infrequently assigns a specific date. Although presented by Pedretti himself as an attempt which further studies can only perfect and enrich, this catalogue provides historians of Leonardo's science and technology with important information from the vast documentation of the Codex Atlanticus, incorporating and relating it with the facts recorded in the Leonardo notebooks that have survived intact, which are often less chaotic and always easier to date.

Thus the goal of following Leonardo's evolution as an engineer and scientist is no longer an unrealizable dream.

Half a century of activity

The following pages are intended to give a general view of Leonardo's career as an engineer on the basis of biographical, documentary, and chronological evidence. We will attempt to reconstruct the commissions that Leonardo received from various institutions and patrons and to specify, date, and characterize the emergence of new interests and working methods, emphasizing the care with which he sought to absorb the experiences of colleagues who had come before him or who were still active during his time. By relating many of Leonardo's technological studies to specific stimuli and occasions, or to the emergence at certain times of an independent need on his part to further his own knowledge, we shall reduce the impression of fragmentariness left by those studies. Leonardo himself will no longer appear as the haughty, aloof genius he has traditionally been presented to be, but rather as a man who was subject to the same needs, expectations, and problems that characterized many other engineers of his day.

The Early Years in Florence (1469-1482)

Leonardo's professional debut as an artist and engineer dates, as is well known, from the time he moved to Florence, almost certainly at the end of the 1460s. Of the few facts we know concerning his early career, one of the most salient — even though it has been unjustifiably questioned — is his apprenticeship in Verrocchio's workshop which, along with that of Pollaiuolo, was the most productive and important in Florence during those decades.[27] The artist's workshop of the Renaissance was characterized by a vast multiplicity of activities. This was particularly true of the workshop of Verrocchio, who was remarkably versatile himself. The Renaissance workshop dealt with architecture, sculpture (including the technical aspects of casting), and painting, not to mention actual works of engineering. There are no specific documents relating to Leonardo's studies and technical activities during the years of his apprenticeship. There remains the testimony of Vasari, who speaks of the emergence, during the years of Leonardo's apprenticeship, of a strong interest in technological questions:

> And he practiced not one branch of art only, but all those in which drawing plays a part; and having an intellect so divine and marvelous... he not only worked in sculpture... but in architecture also... and he was the first, although but young, who suggested reducing the River Arno to a navigable canal from Pisa to Florence. He made designs of flour mills, fulling mills, and engines which might be driven by the force of water: and he wished his profession should be painting.[28]

Vasari's account should be treated with caution, since he might have been thinking of Leonardo's later career and have emphasized in the young Leonardo interests that would be largely present in his mature years. And yet precise elements suggest that Vasari's account is substantially accurate. The Leonardo manuscripts that have survived in their entirety all date from his Milanese years or later, so that they cannot shed light on his earliest activities as an engineer. The only trace of Leonardo's activity in this field during the years of his apprenticeship is recorded in several loose sheets and especially in numerous drawings and notes in the Codex Atlanticus. As early as 1925, Calvi had suggested the possibility of singling out a relevant group of sheets in the Ambrosiana that could be dated to Leonardo's first Florentine period.[29] Subsequently, other important studies enlarged the list of sheets from the Codex Atlanticus which contain notes and drawings from this period.

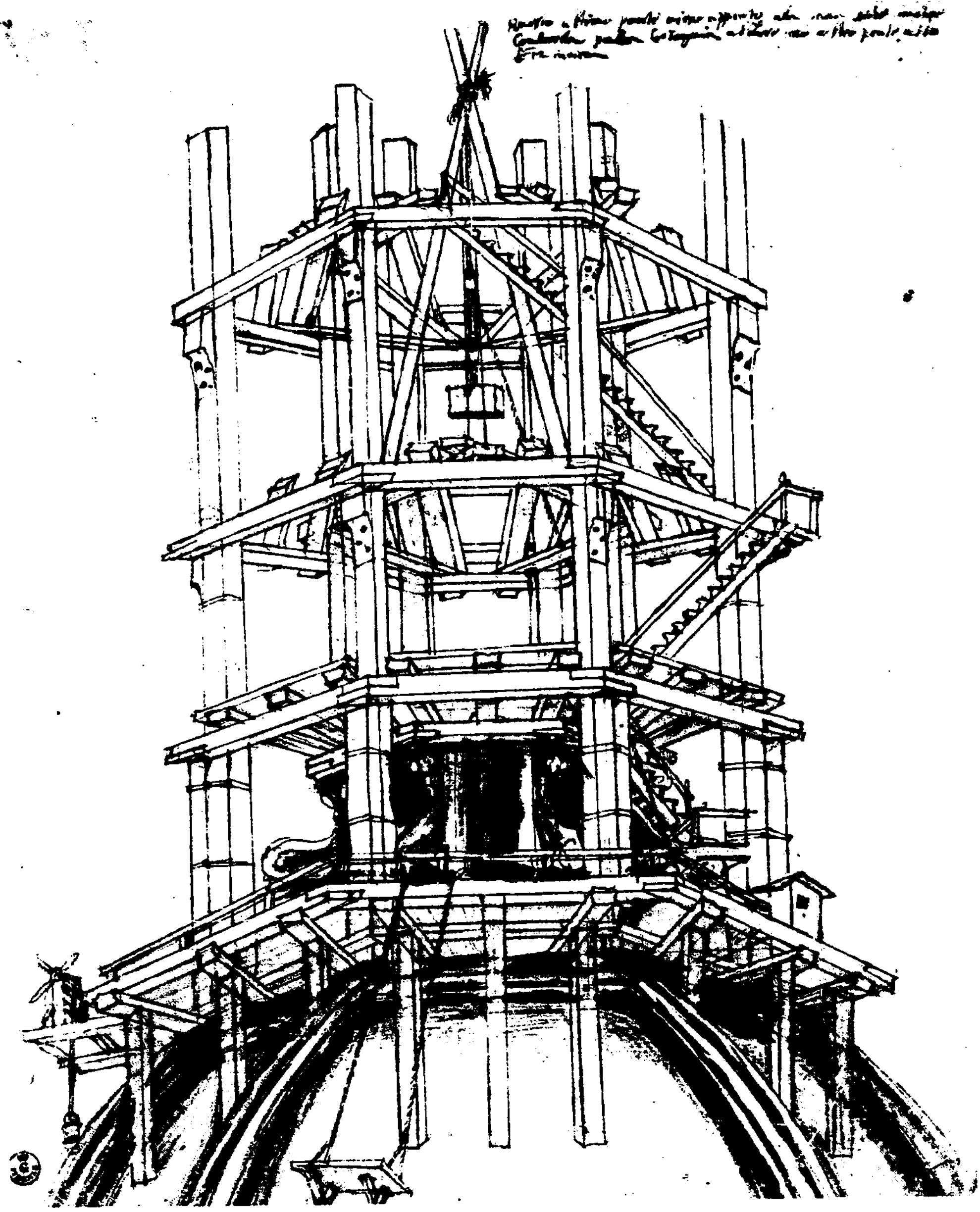


Fig. 26. Gherardo Mechini (c. 1601), Uffizi Gallery, Florence, Gabinetto dei Disegni e delle Stampe, no. 248 A. Drawing of the scaffolding for repairs to the lantern damaged by lightning.

The boldest, most imposing architectural project realized during the fifteenth century in Florence was unquestionably the construction of Brunelleschi's cupola on Florence Cathedral. The undertaking involved great innovations, for the most part conceived and put into practice by Brunelleschi himself. These innovations included not only the masonry courses, which were built without the usual centering, but also the use of several devices that made possible the continual up-and-down movement of workers and materials — materials which were often enormously heavy and had to be lifted to great heights (the upper eye of the cupola is about ninety metres from the ground). Begun in 1420, the work, including the placement of the lantern, was completed by 1461, that is, a few years before Leonardo arrived in Florence.[30] The only operation still to be carried out was placing the large, extremely heavy sphere of gilded copper atop the lantern. We can surmise that when Leonardo entered Verrocchio's workshop at the end of the 1460s, the construction site, a large portion of the machinery, and the scaffolding were still in place (Fig. 26 and Pl. III). And in fact it was to Verrocchio's workshop

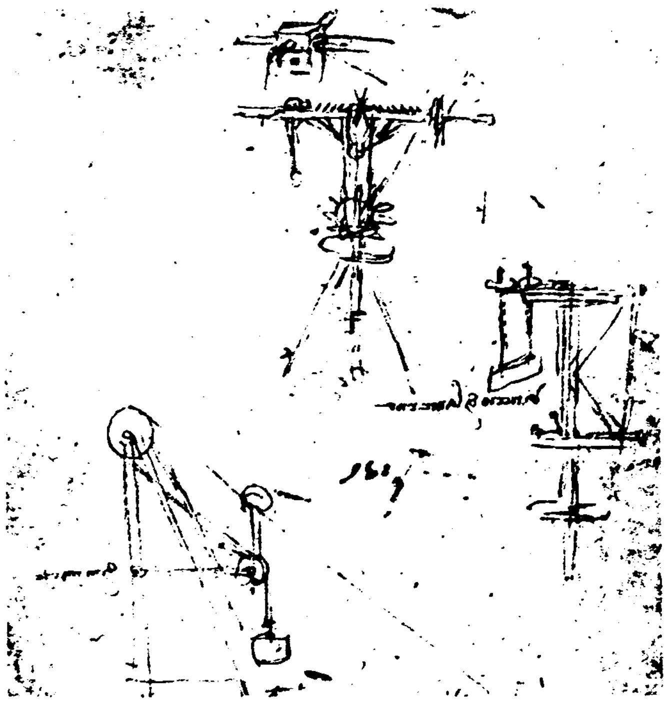
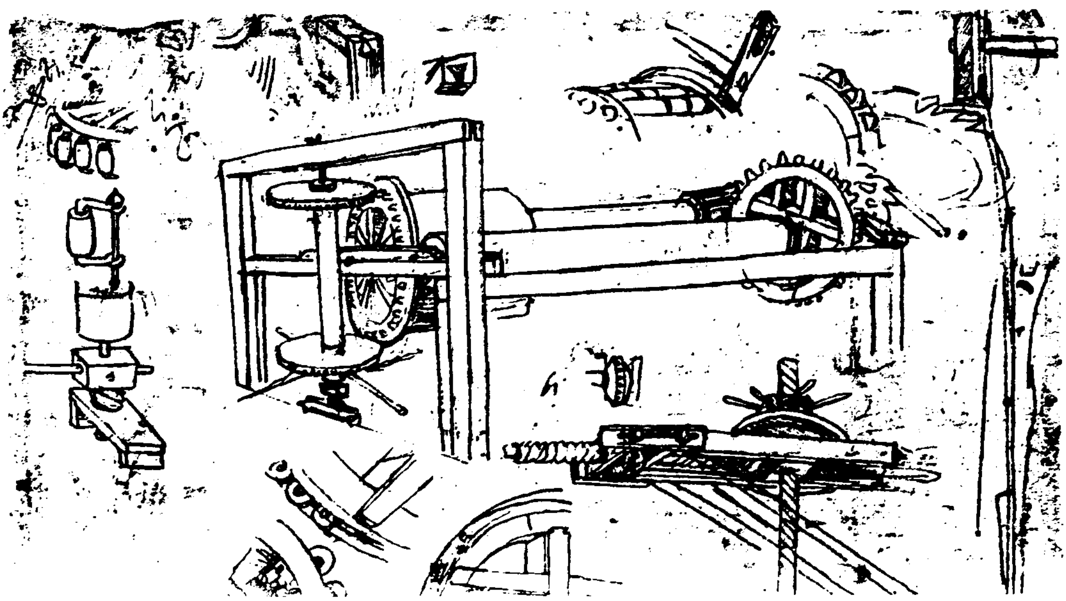
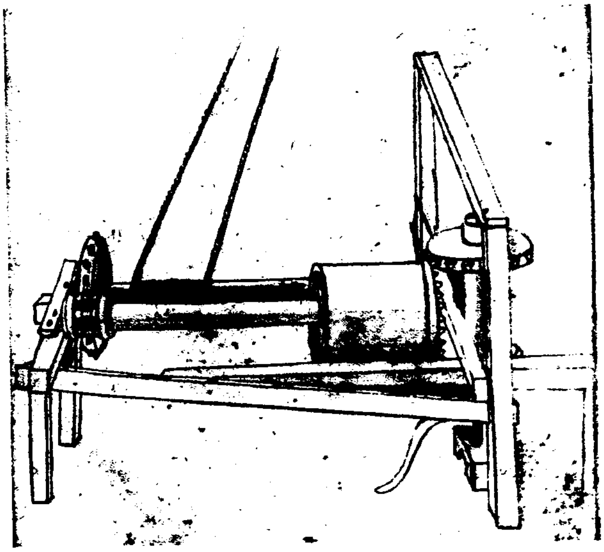


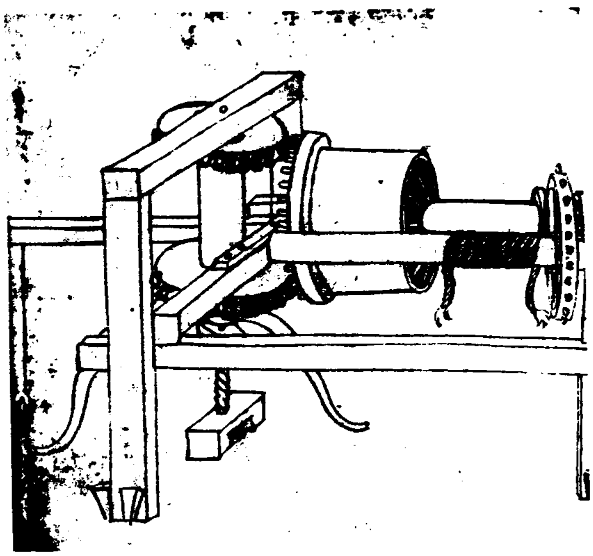
Fig. 27. CA, f. 847 r/309 r-b (detail).

that the preparation of the gilded sphere was entrusted, along with the task of fixing it securely on top of the building, about one hundred metres from the ground.[31] This difficult work was carried out between 1468 and 1472. Proof of any direct participation by Leonardo in this project is lacking, but we have an autobiographical note from a much later time (after 1510) in Paris MS. G: "Keep in mind how the ball of Santa Maria del Fiore was soldered together".[32]

At any rate, it is certain that this achievement of the workshop where he was apprenticed gave Leonardo the opportunity to come into direct contact with the most advanced building technology of the entire Renaissance. Many sheets of the Codex Atlanticus record evident traces of the great impression that Brunelleschi's worksite made on the young Leonardo.[33] He was attracted by the extraordinary ingeniousness of the hoisting machines, of many of which he made careful drawings, as did many of his contemporaries (Francesco di Giorgio,[34] Buonaccorso Ghiberti,[35] Giuliano da Sangallo[36]). On folio 847 r/309 r-b of the Codex Atlanticus, for example, Leonardo drew rapid but

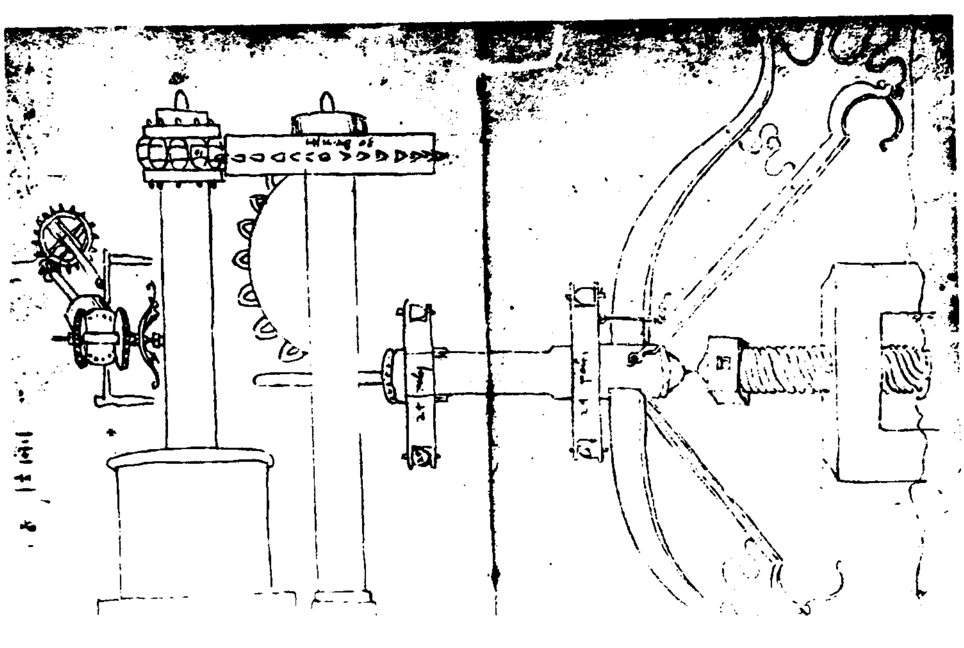


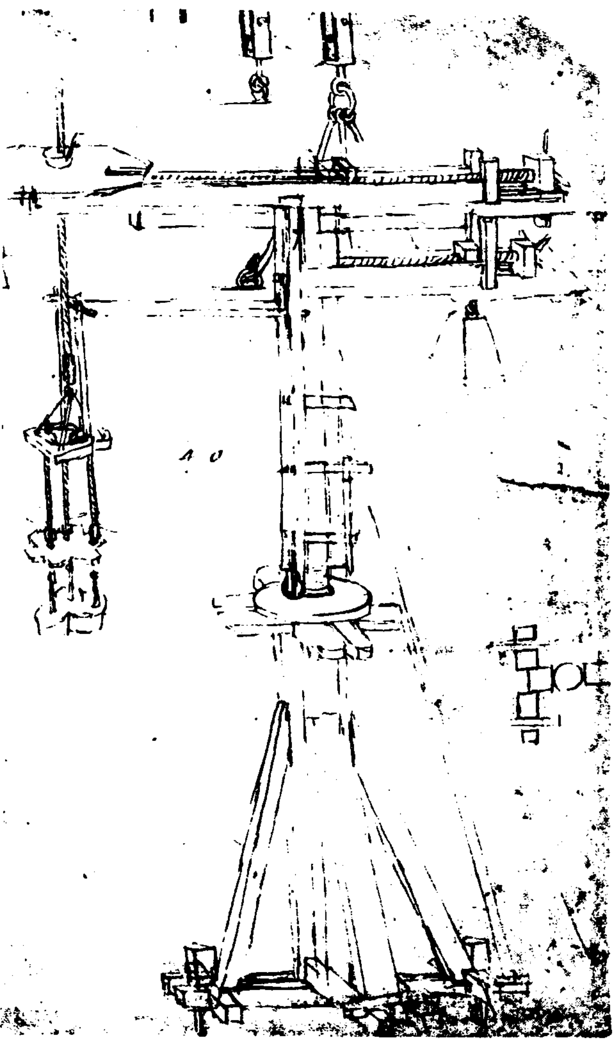




Figs 29 A and B. Buonaccorso Ghiberti, *Zibaldone*, ff. 102 r and 103 v.

very effective sketches of one of Brunelleschi's hoists and two of his cranes (Fig. 27); next to one of the cranes, which is moving a large weight, is the following annotation in the flourishing handwriting characteristic of the young Leonardo: *"viticcio di Lanterna"* ("tendril" of the lantern) to indicate the use of a crane to position the tendril-shaped stones of the buttresses of the lantern. On folio 1083 v/ 391 v-b of the Codex Atlanticus (Fig. 28), Leonardo drew a more precise sketch of another hoist, a comparison of which with similar drawings by Buonaccorso Ghiberti[37] (Fig. 29) and Giuliano da Sangallo[38] (Fig. 30) suggests the large central "*colla*" (hoist) designed by Brunelleschi. This hoist, securely anchored to the ground beneath the cupola and equipped with three speeds (i.e. three different powers) served to lift the heaviest materials and was operated by animal power. In this drawing, which has no accompanying note, Leonardo introduced a technique that would later become habitual for him: he combined a general view of the machinery with a series of drawings of the most important construction details. Here he concentrated on the rotating cogs of the wheel (Brunelleschi's "*palei*" or pivoted gear teeth) and on the screw mechanism which changed the operation from lifting to lowering by inverting the direction of the rotation of the beams. This ingenious solution avoided the considerable nuisance of having to unhitch the animals and hitch them again in the opposite direction.





31. CA, f. 965 r/349 r-a.

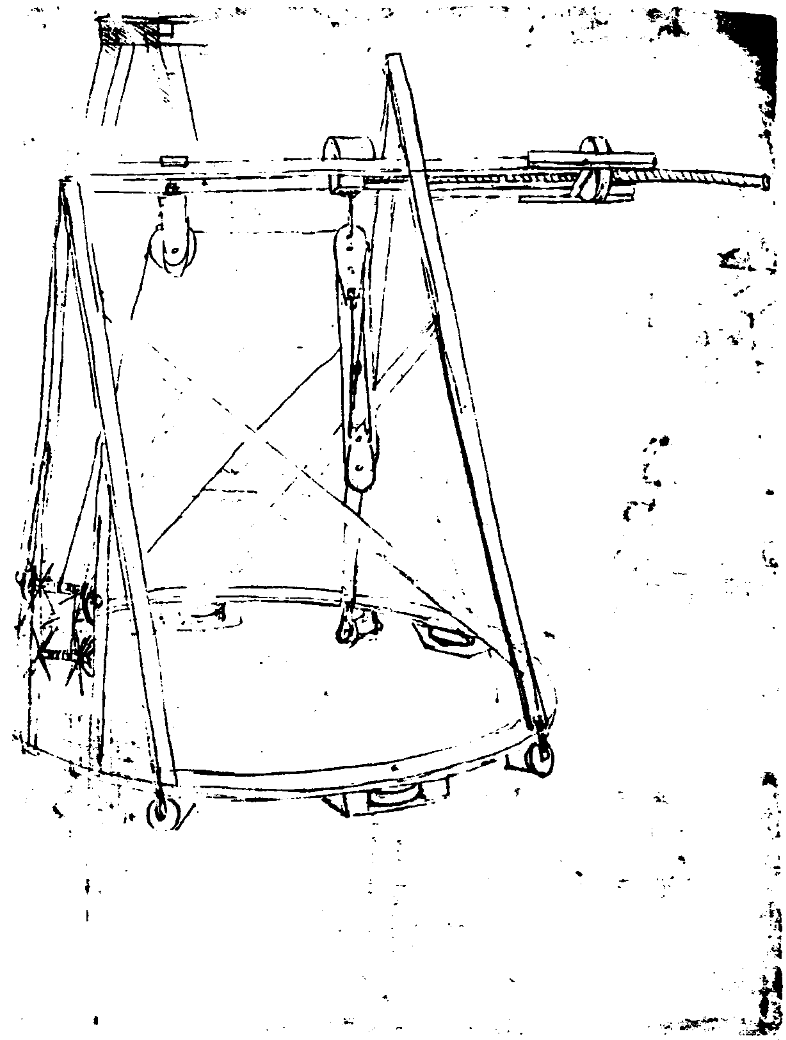


Fig. 32. CA, f. 808 r/295 r-b.

Finally, Leonardo emphasized the positioning of the ratchet wheel, a safety device designed to prevent the overturning of the load in the event of the cogs breaking or of an animal collapsing during the operation of the hoist.

Leonardo's attention was caught by another Brunelleschi machine, the revolving crane placed on the sturdy scaffold erected in the centre of the cupola to carefully position the materials lifted to a certain height by the central hoist; he drew it (CA, f. 965 r/349 r-a: Fig. 31) using the same technique of combining an effective general view with a study of several construction details. He also did careful drawings (CA, ff. 808 r and v/295 r-b and v-b: Fig. 32) of the revolving annular platform crane that can be progressively raised by turning four screws, a device designed by Brunelleschi and used in the construction of the lantern of Florence Cathedral. Other Leonardo drawings (CA, f. 105 Bv/37 v-b: Fig. 33; and f. 138 r/49 v-a: Fig. 34) that can be dated around the same time on the basis of style and handwriting, record his recollection of other machines from Brunelleschi's worksite (the light hoist, the carriage-mounted crane, and a screw-operated hoist). They indicate the attention with which he studied the form and operation of single and multiple turnbuckles and lewises (CA, f. 1078 Bv/389 v-b and 926 v/339 v-a), ingenious construction accessories widely used by Brunelleschi. This group of drawings, which Gustina Scaglia[39] and Ladislao Reti[40] identified, does not appear to be a matter of Leonardo simply copying the drawings of the same devices from the notebooks of contemporary

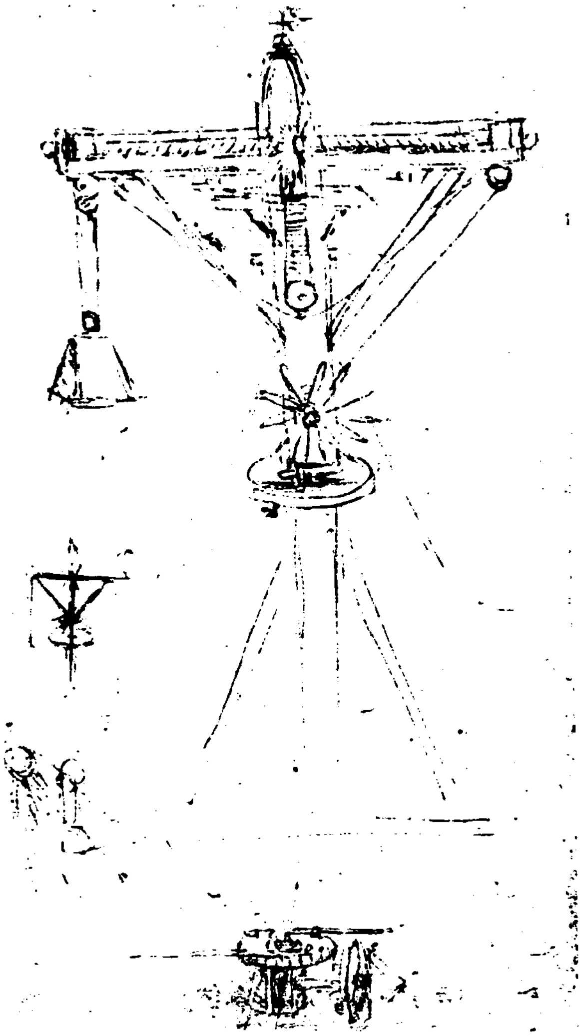


Fig. 33. CA, f. 105 Bv/37 v-b. Brunelleschi's elevator and light hoist (bottom).

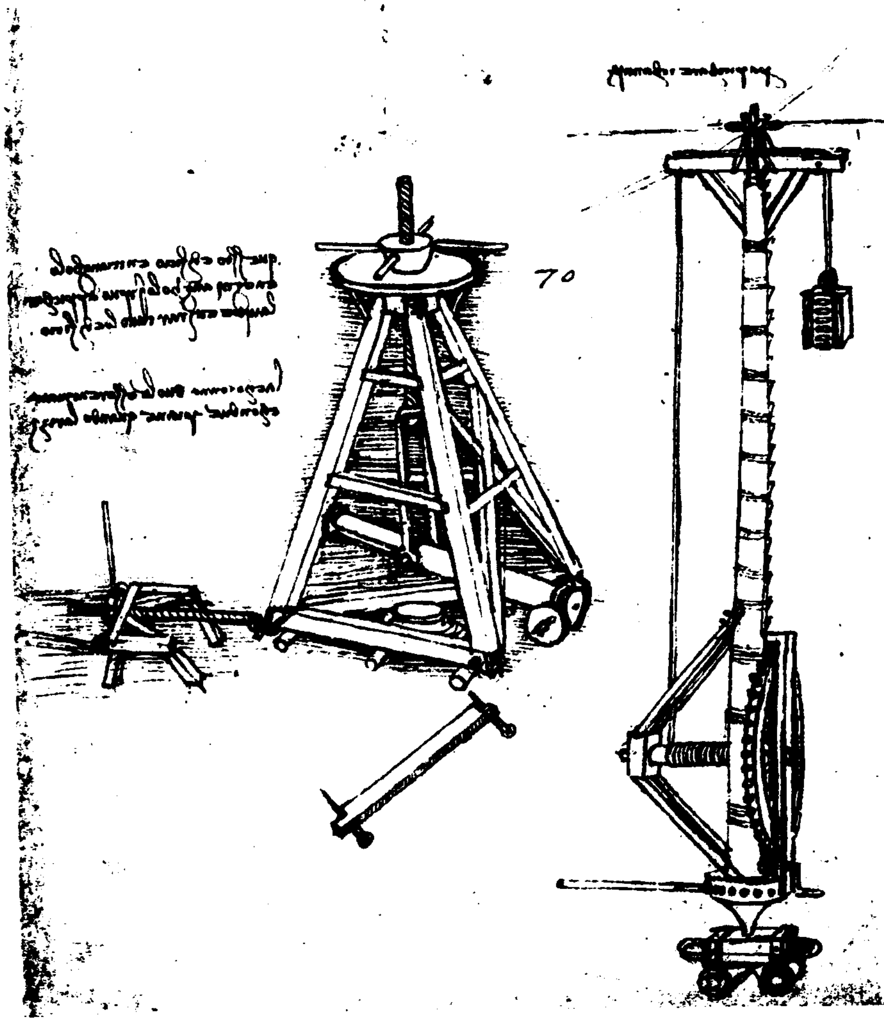
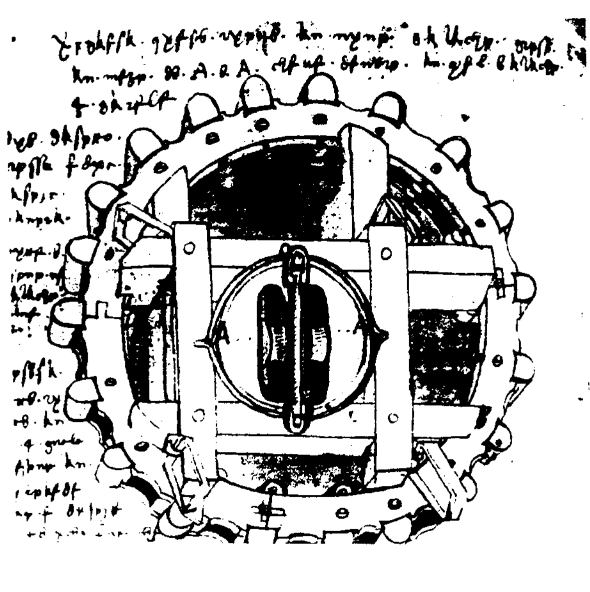


Fig. 34. CA, f. 138 r/49 v-a. Carriage-mounted crane.

engineers, such as the *Zibaldone* of Buonaccorso Ghiberti (Fig. 35) or Giuliano da Sangallo's *Taccuino Senese*. Richer in details and made from different points of view, Leonardo's drawings appear to derive from a direct experience of the actual machines. As we have said, it is highly likely that Brunelleschi's technological monuments were still in operation or, in view of their extremely high cost, had been kept for future use in the warehouses of the Opera del Duomo, to which it would not have been difficult to gain access for a member of the workshop commissioned to carry out the final work on the cathedral.



Reti did not attempt to date this group of studies, although he did place them during Leonardo's first Florentine period. Pedretti, on the basis of the ductus of the handwriting and the style of the drawings, dates them 1478-80.[41] I believe that their dating could even be moved back a few years to the time (1468-72) that the gilded copper ball for the top of the lantern was being prepared in Verrocchio's workshop.

The proposed earlier dating of this particular group of drawings emphasizes the extraordinary importance of Brunelleschi for the early years of Leonardo the engineer. Brunelleschi must surely have been a model for the inexperienced young Leonardo. And indeed, other documents from these years unequivocally indicate Leonardo's interest in Brunelleschi and the pains he took to familiarize himself with his works.

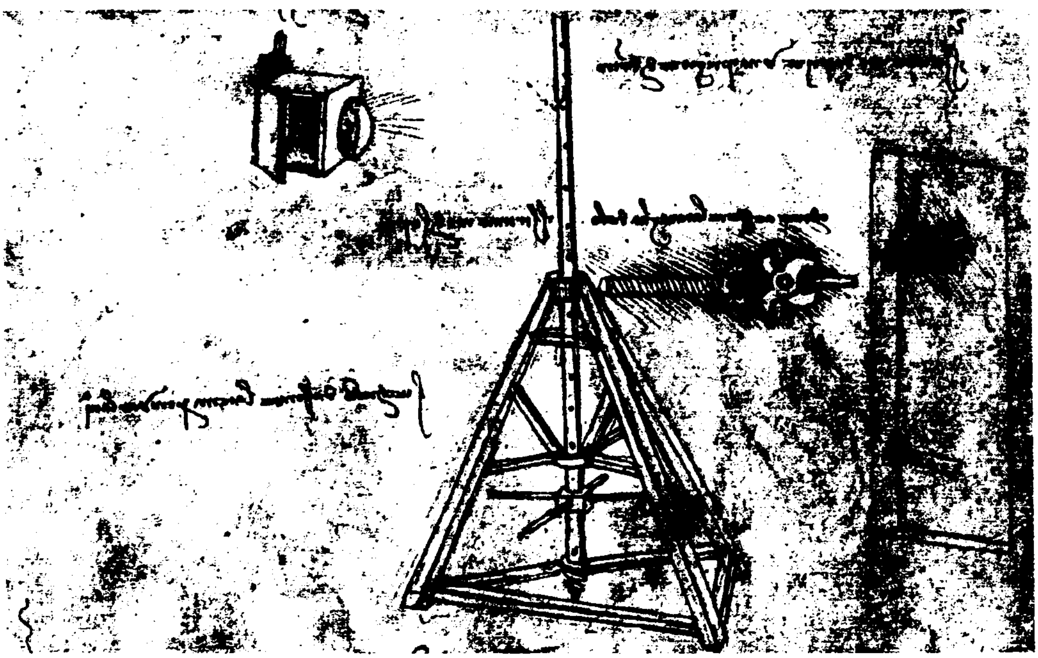


Fig. 36. CA, f. 34 r/9 v-b (detail).

On a sheet of the Codex Atlanticus that can be dated 1480 (f. 34 r/9 v-b: Fig. 36), Leonardo illustrated a screw device for "opening a prison from inside". Another sheet from about the same time shows an instrument for removing the heavy bars of a window. This is a screw jack, which is almost identical, except for its transversal arrangement, to the "Brunelleschian" screw hoist of which Leonardo made a drawing during the same years on folio 138 r/49 v-a of the Codex Atlanticus. These are specific examples of Leonardo's immersion in Brunelleschi's technology and of his early attempts to use it in different fields and for new solutions. He was particularly attracted by the device of the screw, with its extraordinary manoeuvrability and enormous power. For Leonardo, the graceful movement of the coils of this device seemed to reproduce the living forces of Nature itself, the force of whirlwinds and winds, of the water vortexes which Alberti had compared to a "liquid drill".[42] As in Brunelleschi's machines, the screw seemed to Leonardo to promise an endless multiplication of power.

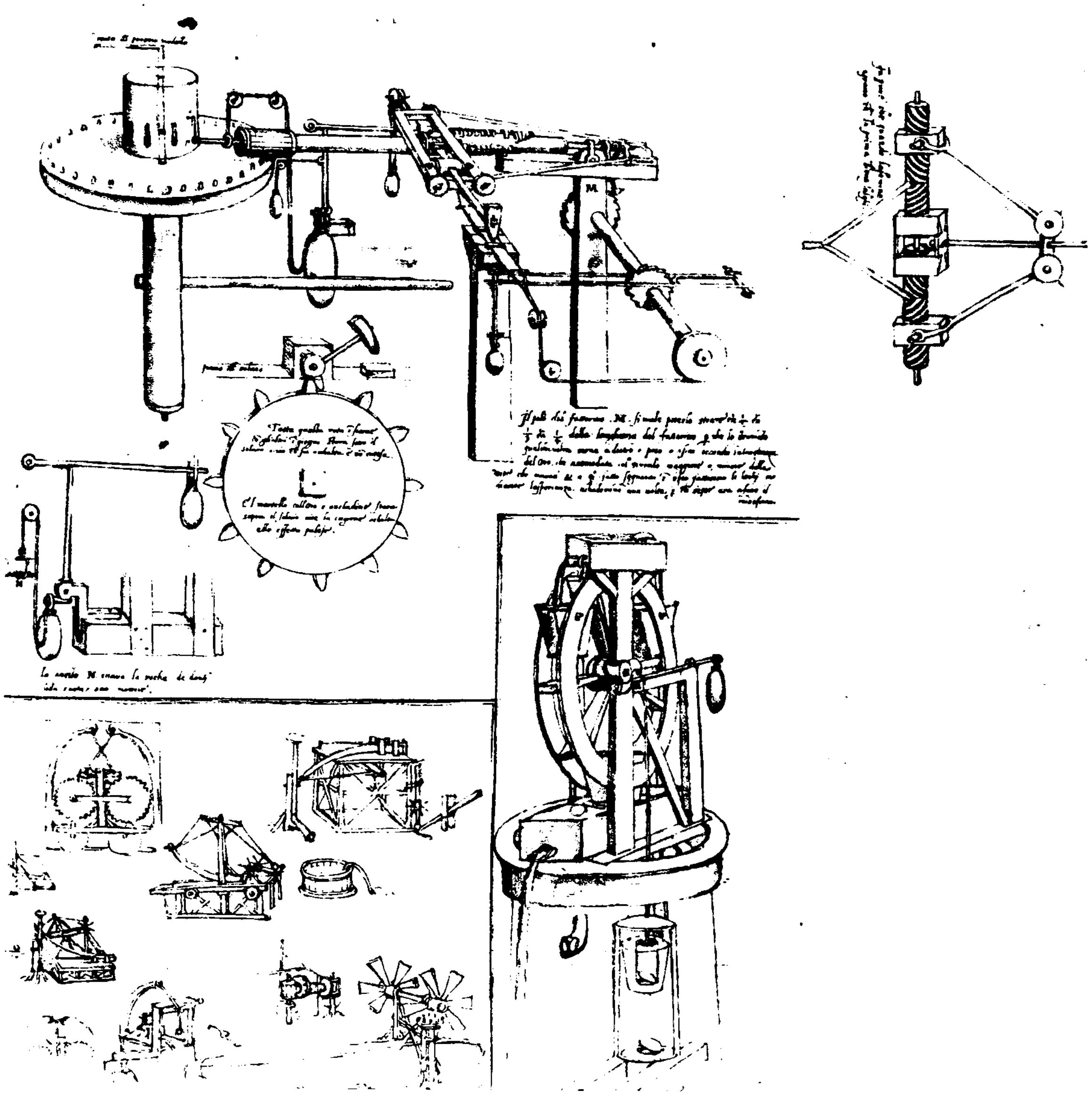
Fig. 37. CA, f. 909 v/333 v. "Underwater attacks".

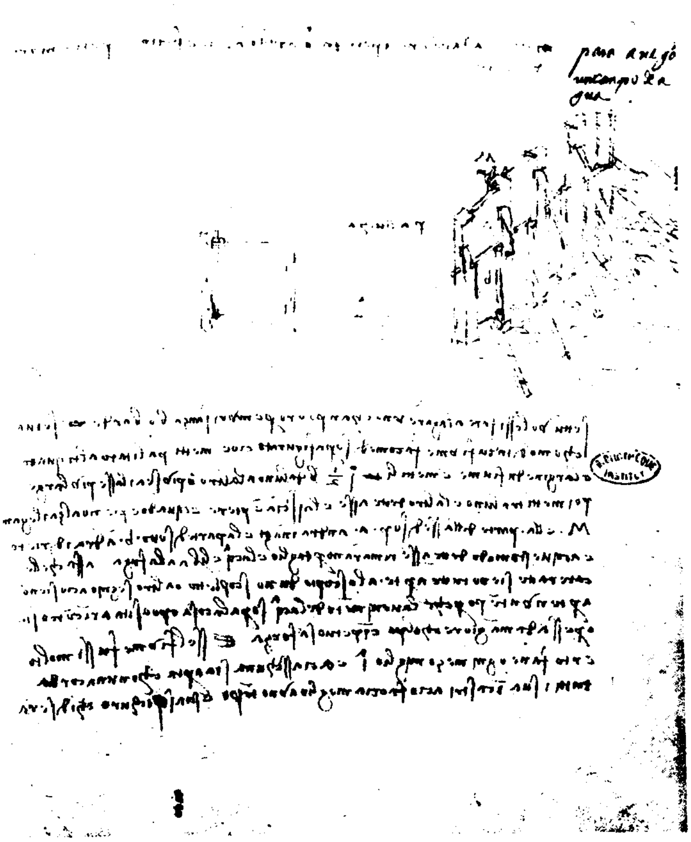
And its uses were universal. On a famous sheet of the Codex Atlanticus (f. 909 v/333 v: Fig. 37), traditionally linked to Leonardo's visit to Venice in 1500 but actually belonging to the early years of his first Milanese period, there are drawings and notes on "underwater attacks" and devices for breathing underwater. Leonardo refers here to an invention from which he expected to derive considerable financial gain. The text and drawings are deliberately obscure (Leonardo is protecting his secret) and it is not easy to understand whether he is thinking of frogmen or of a submarine vessel that would allow men to go unseen beneath the keel of enemy ships and sink them with a drill-like instrument of which there are several sketches on the sheet. Leonardo writes: "You need to take an impression of one of the three iron screws of the Opera of Santa Liberata". Santa Liberata is, of course, Santa Maria del Fiore (Florence Cathedral), and the reference, as confirmed by the drawing, is to Brunelleschi's turnbuckles (intended primarily to maintain the tension of ropes and cables) which

Leonardo had already sketched on another sheet.[43] Thus we have here an original use of the screw and another eloquent reference to the influence of Brunelleschi. We can perhaps trace another echo of this in a Leonardo project from these years which is mentioned by Vasari:

> And among these models and designs there was one which he often demonstrated to many ingenious citizens who were then governing Florence, how he proposed to raise the Temple of San Giovanni in Florence, and place steps under it without damaging the building...[44]

Pedretti considers Vasari's account to be reliable. He has analyzed this problem with his usual acuteness and documentary thoroughness, attempting to imagine the procedure devised by Leonardo to raise a monument the size of the Baptistery. According to Pedretti, we can presume that Leonardo intended carefully digging until the foundations of the building were exposed and then constructing underneath it a firmly attached platform, to be raised with "the use of huge screws placed perpendicularly under that platform and activated simultaneously".[45] Here again we have a project that is Brunelleschian in spirit in which the technology of the screw plays a decisive role. To again





ig. 39. Paris MS. B, f. 64 r.

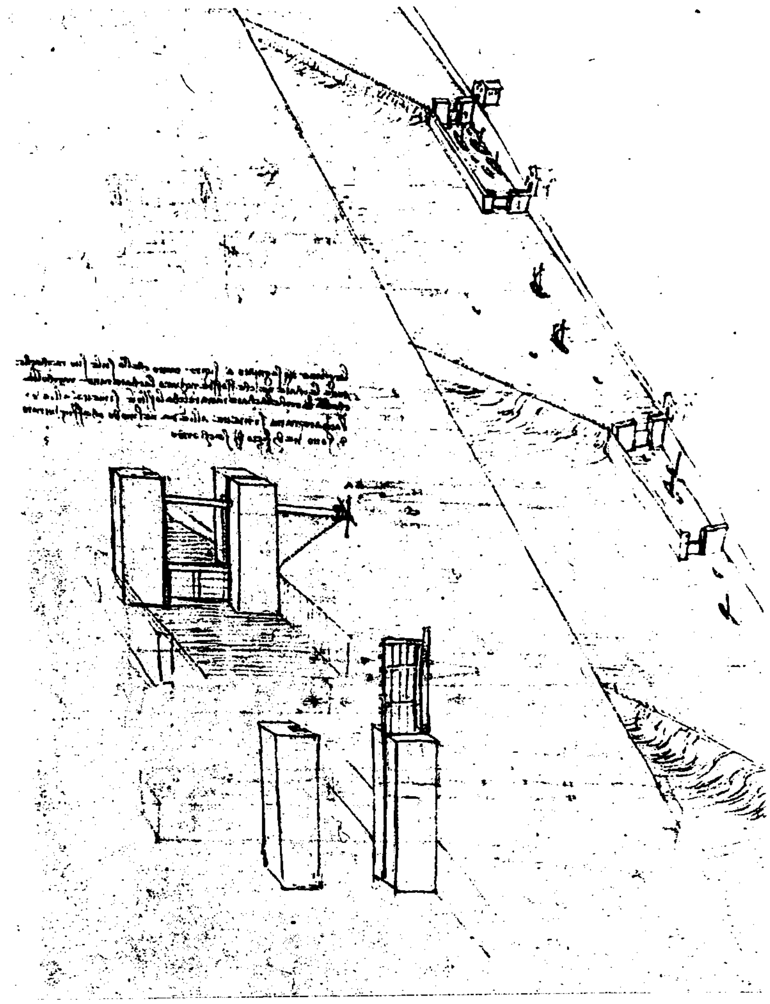


Fig. 40. CA, f. 90 v/33 v-a.

quote Vasari: "...and by means of levers, windlasses and screws he showed the way to raise and draw great weights".[46]

It is Vasari, as we have already said, who informs us of the young Leonardo's projects regarding the Arno River, both to make it navigable from Florence to Pisa, and to use it as a source of energy for industrial purposes. No studies by Leonardo from this period dealing with the problem of the canalization of the Arno have come down to us, although Pedretti has recently drawn attention to a sheet of sixteenth-century copies of Leonardo drawings (Fig. 38 and Pls IV-V) which include a paddle-wheel boat that might preserve a memory of the *badalone*, the riverboat designed by Brunelleschi.[47] Another, more specific echo of Brunelleschi, this time related to problems of river canalization, is in Paris MS. B (f. 64 r: Fig. 39), which contains studies from the early years of Leonardo's first Milanese period (1485-90). In the context of a series of drawings and annotations of military technology and strategy (in particular the way to deviate the natural course of a river in order to flood an enemy city or encampment), Leonardo inserted a reference, that has only recently been deciphered, to a hydraulic engineering project of Filippo Brunelleschi: the ill-fated attempt to deviate the Serchio River in order to flood the city of Lucca and force it to surrender, a project put into operation by Brunelleschi in 1428 during the war between Florence and Lucca.[48] Another study that can be related to canalization problems is the sketch of a cataract on folio 90 v/33 v-a of the Codex Atlanticus (Fig. 40) which can be dated 1480-2.

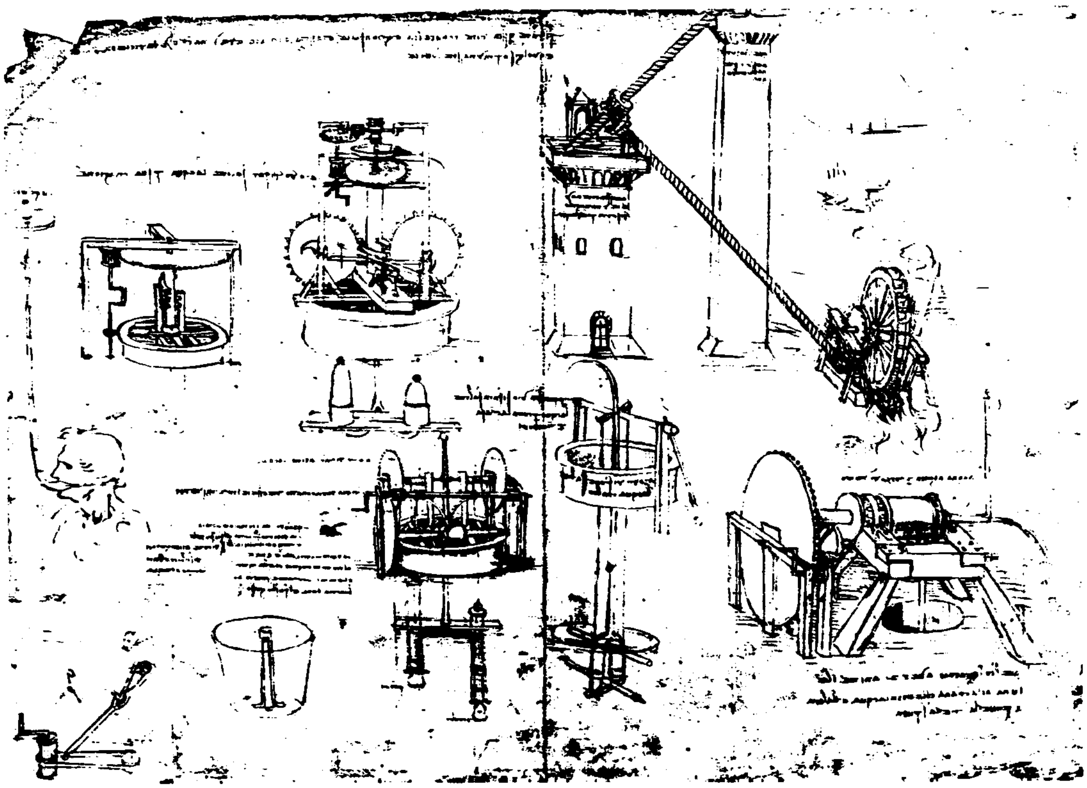
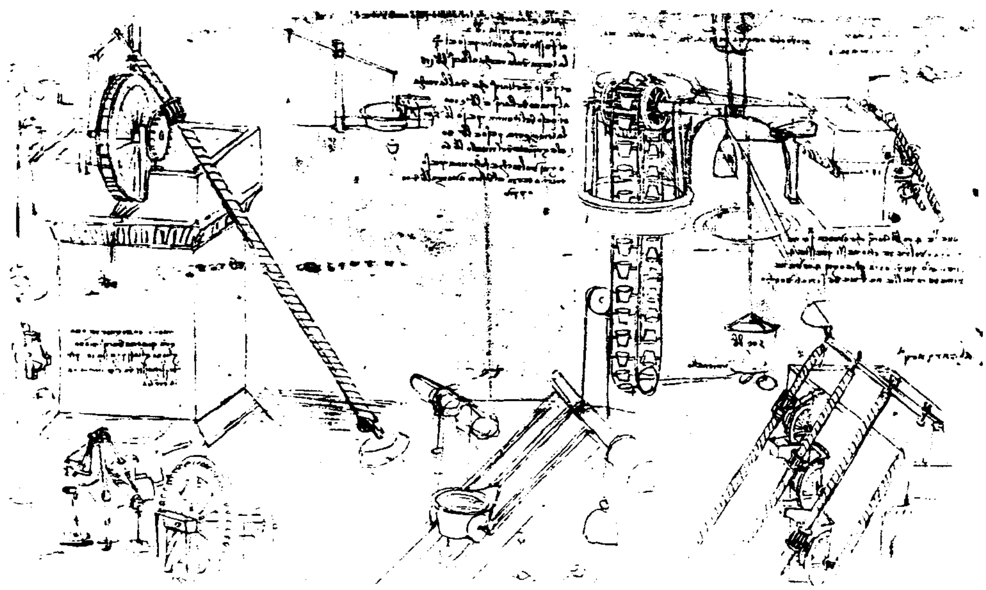


Fig. 41. CA, f. 1069 r/386 r-b.

There is further evidence of Leonardo's early interest in hydraulics. In a famous memorandum (CA, f. 888 r/324 r), probably written in 1482, shortly before he moved to Milan, Leonardo listed the works that he intended to leave in Florence and the ones he was taking with him to Milan.[49] The list, along with numerous references to drawings and paintings he had done in Florence, also mentions "certain instruments for ships" and "certain water instruments". The "instruments for ships" can be related to the studies of underwater attacks mentioned above. But many sheets of the Codex Atlanticus dating from Leonardo's first Florentine period attest to the attention he gave to "water instruments" from the very beginning of his career. The entire sheet (CA, f. 1069 r and v/386 r-b and v-b) contains a remarkable number of hydraulic devices (Figs 41–42 and Pl. I). There are various types of pump and an illustration of the combined use of two Archimedes screws, activated by a wheel



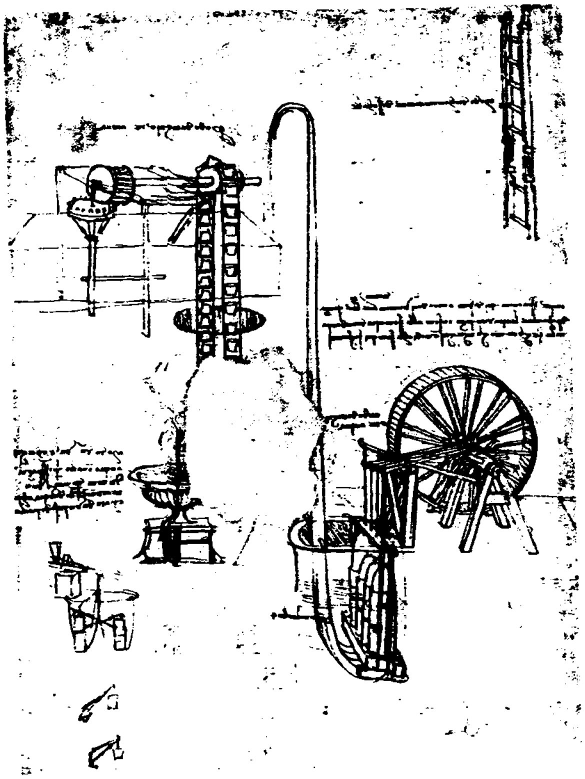


Fig. 43. CA, f. 7 r/1bis v-a.

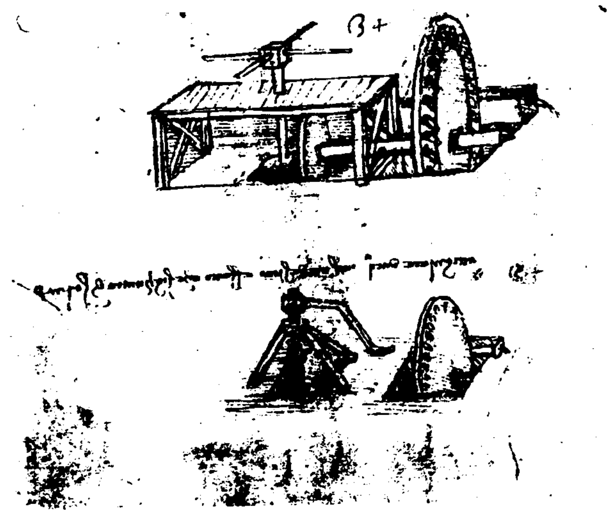
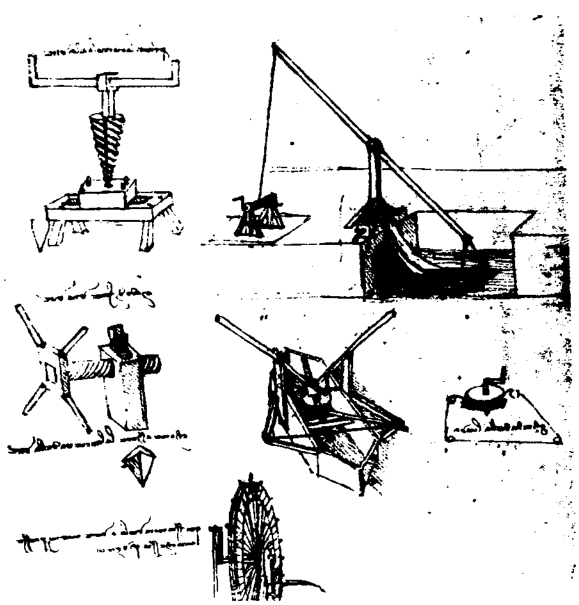


Fig. 44. CA, f. 34 r/9 v-b (detail).

turned by a river, which raise the water to the tops of two towers. The problem studied by Leonardo here is that of raising water from wells or water courses in order to then use its fall as a source of energy. These drawings, which still reflect Leonardo's immature style, reveal that he was beginning to experiment with new solutions: he shows, as in an X-ray, the underground mechanisms of the double-action pump, and renders with great precision complex wheelworks in which we can recognize an attempt to transform a constant circular thrust into an alternating motion. On the sheet in question we also find a drawing of a siphon, a sketch illustrating a method for breathing underwater, and, on a separate fragment, a diagram of a mechanism for a flying machine. Another sheet from the same time (CA, f. 7 r/1 bis v-a) reflects the same interests (Fig. 43): a siphon, a double-action pump activated by a large paddle wheel which can raise water to a great height, and a machine for raising the



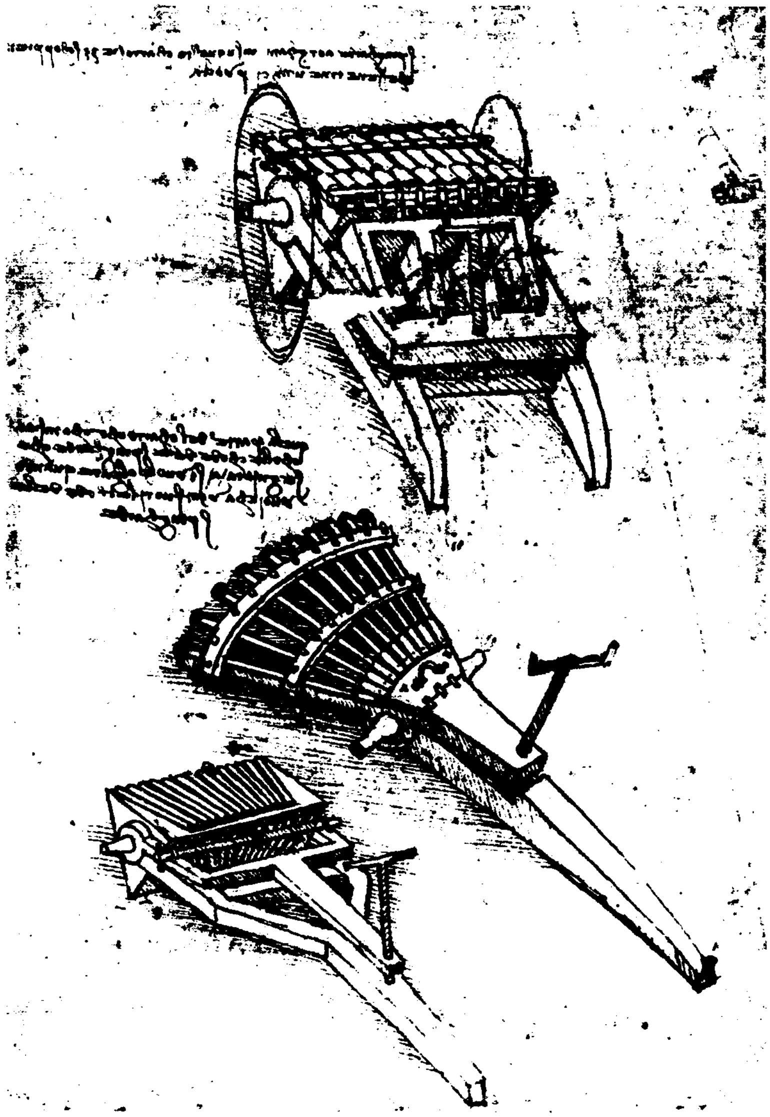
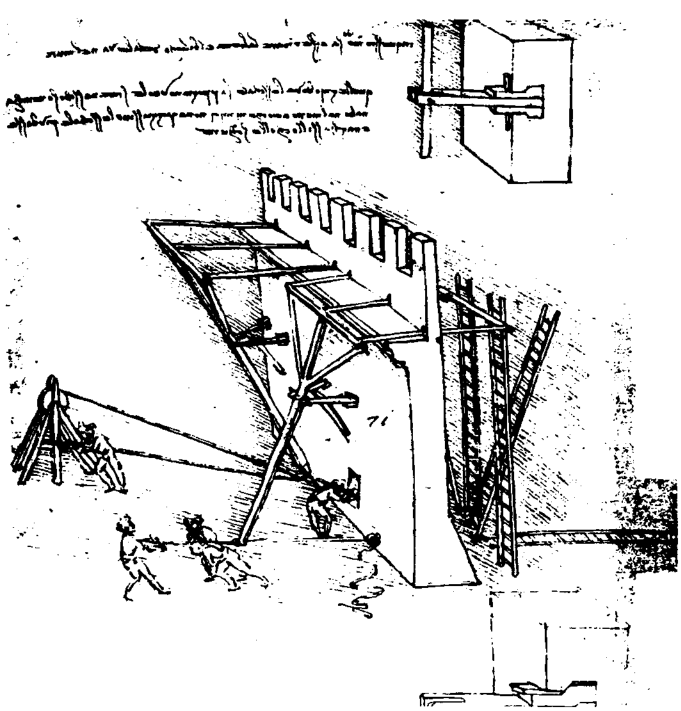
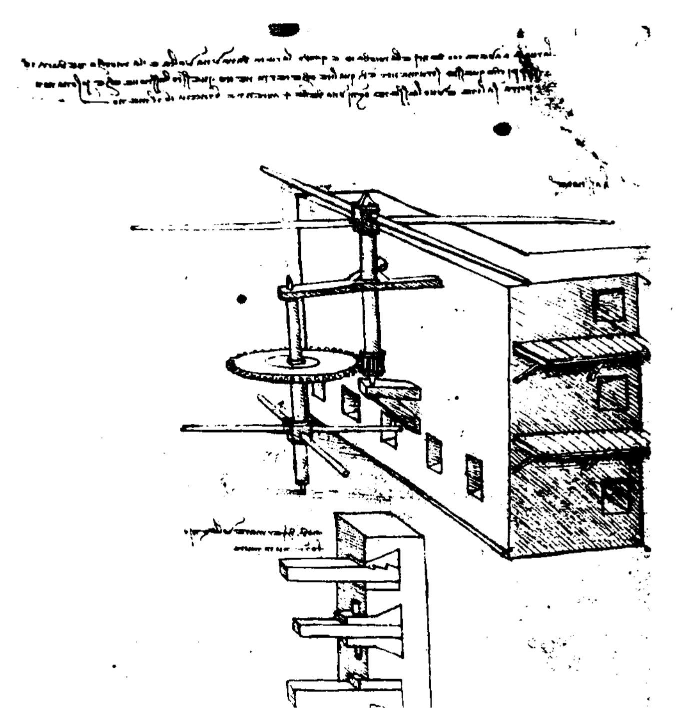


Fig. 46. CA, f. 157 r/56 v-a.

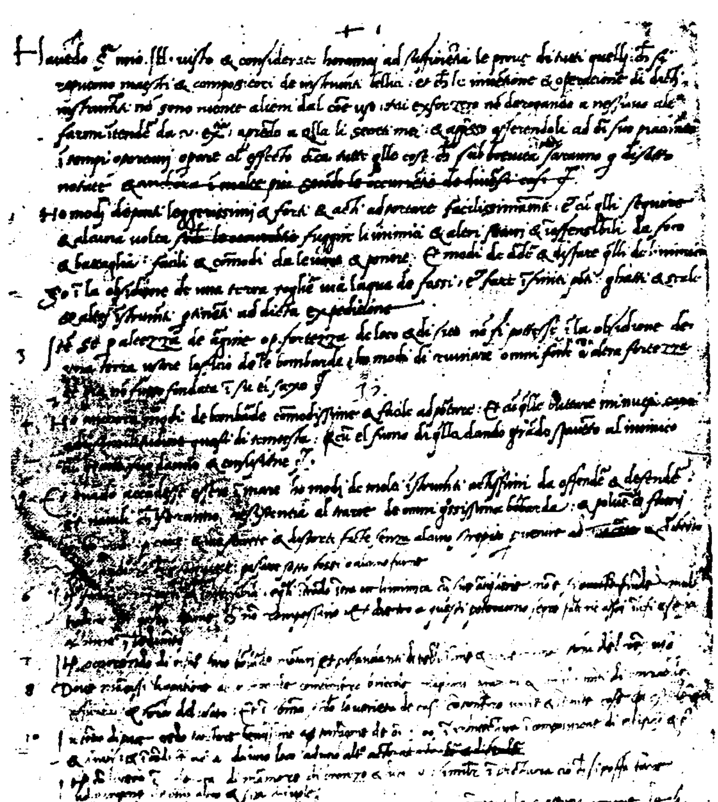




water from a pond by means of the continual movement of a conveyor belt with buckets that are filled by immersion in the well and emptied into a reservoir placed above. This sheet is obviously related to the one mentioned above (CA, f. 34 r/9 v-b: Fig. 44) on which there are sketches of other paddle wheels with buckets, as are other sheets of the Codex Atlanticus (for example f. 156 r/56 r-b: Fig. 45).

Another set of interests which clearly emerges from Leonardo's early sheets is related to military technology. Although, as Pietro Marani has shown,[50] Leonardo's interest in military architecture increased when he went to Milan, he had begun to focus on military technology while still in Florence. From this period we have studies of mortars and small bombards (*scoppietti*) of various types (CA, f. 157 r/56 v-a: Fig. 46; f. 167 r/59 r-c). These constitute specific evidence of Leonardo's effort to perfect himself in one of the most important areas of activity of the Renaissance engineer, which guaranteed steady work opportunities and high pay. Leonardo studied not only systems of attack, but also the use of mechanical devices for defence. To this category belong two progressively elaborated studies, which can be dated to about 1480, of techniques for defending a fortress in the event of the enemy scaling its walls. Leonardo constructs an almost cinematic sequence here. First he illustrates how to push away the enemy ladders by means of a movable protective outer railing (CA, f. 139 r/49 v-b: Fig. 47). Then, in the event that the enemy soldiers succeed in overcoming this first obstacle, he indicates, again with careful precision (CA, ff. 1039 r/372 v-b, and 94 r/34 v-a), an easy, spectacular method of sweeping them off the walls by rapidly rotating horizontal poles (CA, f. 89 r/32 v-a: Fig. 48). As in so many other cases, the novelty here consists in the use of well-known devices for a new purpose; in fact, Leonardo's solution depends upon a mechanical structure that is identical to that of a mill.

This specific evidence shows how in Leonardo's famous, much-discussed letter to Lodovico Sforza of 1482, in which he lists the various services he is able to offer, the references to his abilities as



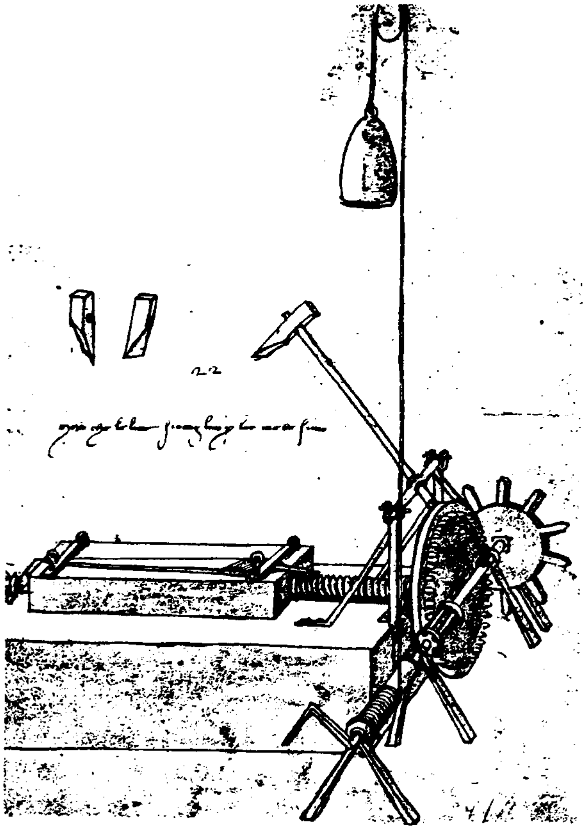


Fig. 50. CA, f. 24 r/6 r-b.

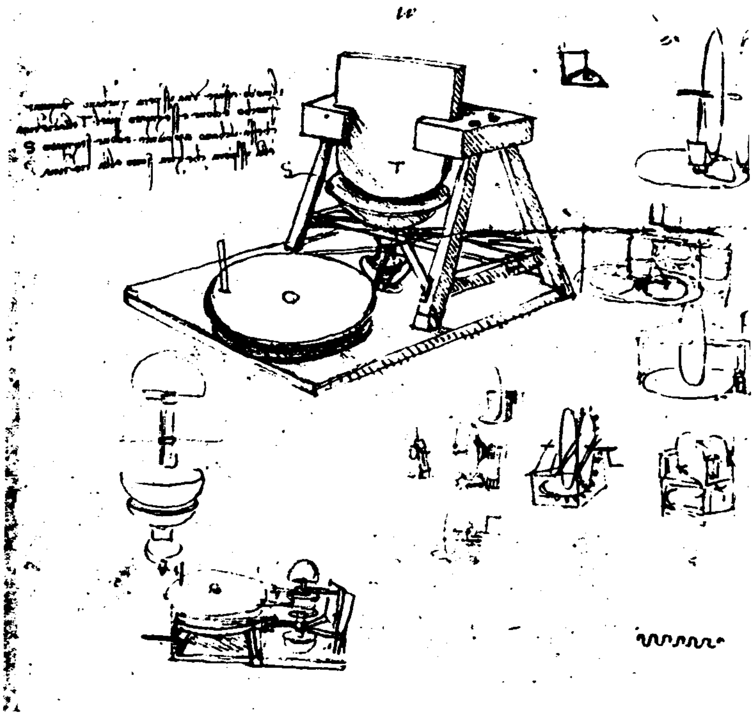
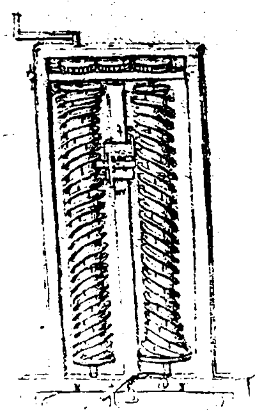
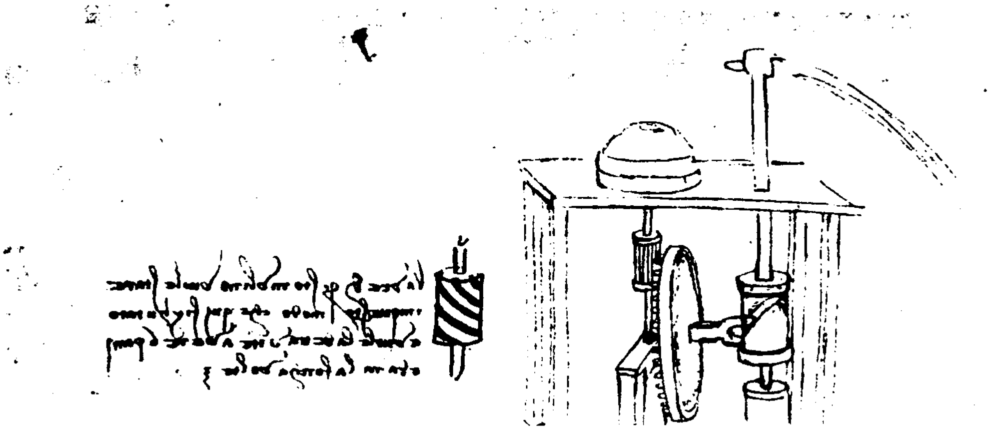


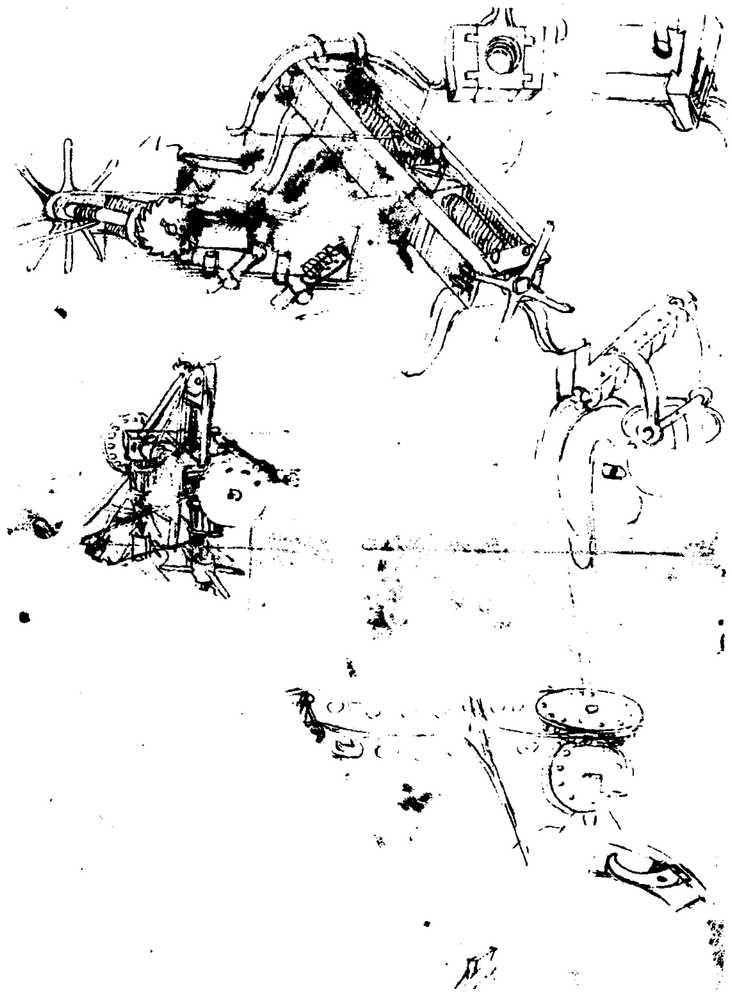
Fig. 52. CA, f. 17 v/4 v-a (detail).

a military engineer, albeit deliberately exaggerated, were not merely idle boasting. Although he was still lacking in practical experience, Leonardo had indeed reflected upon "new types of chariots", "covered ways and ladders and other instruments", the way to "take the water out of trenches", "bombards, mortars, and light ordnance of fine and useful forms, out of the common type" (CA, f. 1082 r/391 r-a: Fig. 49). Thus it was with some justification that Leonardo offered his services as an advisor to an aggressive, bellicose lord, not only for works of peace but also in time of war.[51]

Other studies in the Codex Atlanticus dating from Leonardo's early years in Florence show that he was studying various industrial machines. Suffice it to mention the machine for the production of files, on a sheet from about 1480 (CA, f. 24 r/6 r-b: Fig. 50). We have no proof that this was an invention of Leonardo's, but at any rate it is evidence of his interest in the mechanization of production methods that had formerly been carried out manually (see also Leonardo's later drawing for the mechanical filing of screws in Madrid MS. I, f. 15 r: Fig. 51). There are other studies, that can be dated 1478-80 (CA, ff. 17 v/4 v-a: Fig. 52; 1057 v/380 v-b), of machines for producing concave







g. 54. Uffizi Gallery, Florence, Gabinetto dei Disegni e
·lle Stampe, no. 446 Ev [f. 7 v].

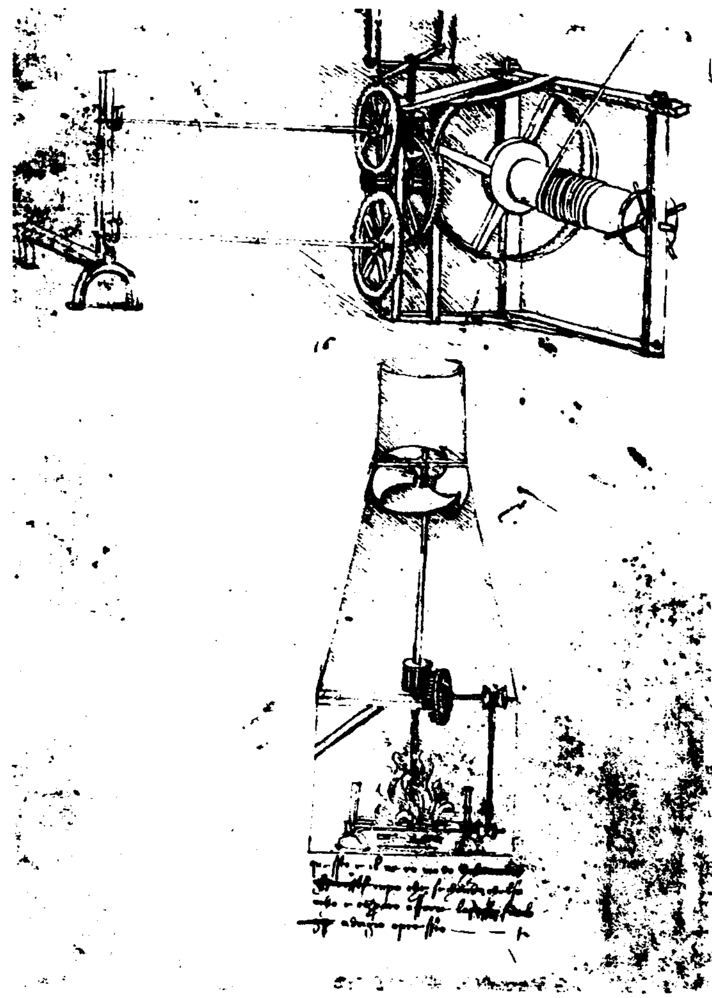


Fig. 55. CA, f. 21 r/5 v–a.

mirrors, perhaps to be used as burning mirrors for soldering. Also worthy of attention are Leonardo's drawings of mills (CA, f. 1084 v/391 r–b: Fig. 53), of hoists, and of the screw mechanism for bending a catapult on the verso of an Uffizi sheet that can be dated 1478 (Fig. 54), and, finally, the drawing of two spits, one activated by a weight and the other by hot air, on folio 21 r/5 v–a of the Codex Atlanticus (Fig. 55). These spits, which were not invented by Leonardo, show how his attention was attracted by complex rotary systems that could adapt any source of energy (water, weight, air) to any imaginable use.

Leonardo's technological studies from this time do not have any particular coherence or continuity. They appear to be a series of "cases" analyzed in a practical fashion. Nor is there any surviving evidence that Leonardo attempted to relate these practical studies to general principles. Like his colleagues from the fascinating but limited world of the Renaissance workshop, Leonardo learned by experience to use natural and animal power; but the typical Renaissance engineer did not attempt to understand the nature of that power, nor to establish its use on a quantitative basis. Not even the great Brunelleschi had broken out of this mould, in spite of the fact that on more than one occasion he had felt the need to utilize the knowledge and mastery of geometry of a learned humanist like Paolo del Pozzo Toscanelli, one of the protagonists of the fifteenth-century Archimedean revival.[52] Toscanelli is also remembered in a note that can be dated 1480 (CA, f. 42 v/12 v–a) — "*Maestro Pagholo Medico*" (Master Paolo the Physician) — which probably preserves the evidence of Leonardo's intense effort to come into contact with the aged physician and mathematician. This is further confirmation of the influence of Brunelleschi, an influence that dominated the years of Leonardo's technical apprenticeship.

Leonardo in Milan (1482-1499): Continuity and Renewal

The letter to Lodovico Sforza mentioned above presents the "curriculum" of an engineer who was naturally concerned with emphasizing his most attractive capabilities for the patron he wished to serve. This explains why the accent of the letter is primarily on architecture and military technology, which were essential for furthering Lodovico's plans for expansion. In fact, in this letter civil technology is relegated to a secondary level; Leonardo mentions it only once, to emphasize his ability to direct water from one place to another. Finally, he states that he is a qualified sculptor and founder, in response to a specific desire of the duke — to erect a gigantic equestrian monument in memory of Francesco Sforza — a desire concerning which Leonardo was apparently well informed.

Whatever the reasons that led Leonardo to leave Florence, in 1482 he entered the service of the largest, most active and powerful court on the Italian peninsula, led by an ambitious lord who governed a territory full of natural resources and industrial activity, at the centre of which was the city of Milan, a real metropolis (it had a population of approximately 200,000, more than twice that of Florence). The Duchy of Milan could thus offer an ambitious, eclectic young man like Leonardo the opportunity to display his brilliance in a number of areas.

After arriving in Milan as an artist with a good reputation but not yet famous, Leonardo soon succeeded in making his extraordinary qualities known. He was given duties and specific commissions by the duke both as an artist and as an engineer. We do not know the amount of the regular salary he received until 1500, nor the exact contractual terms binding him to Lodovico. In documents of the time he is mentioned as "*ingeniarius ducalis*" and "*ingeniarius camerarius*". It is also certain that he was permitted to accept commissions from private parties, and in fact he took on several, both of an artistic and of a technical nature.[53]

Year by year the reconstruction of Leonardo's activity becomes less difficult. The available documentation increases and, in addition to the Codex Atlanticus, we have other precisely datable manuscripts which present a greater coherence of interests. This is the case of Paris MS. B and the Codex Trivulzianus,[54] both compiled during the second half of the 1480s in Milan. These two manuscripts are also similar in terms of their main thematic nuclei. In Paris MS. B and the Codex Trivulzianus, in fact, there is particular emphasis on architectural studies and studies of military technology, confirming that Leonardo took very seriously his duties as technical-military advisor, which fundamentally was the capacity in which he had offered his services to Lodovico. These are famous studies, which have been the object of much analysis even in recent times, analysis that presents Leonardo as a great but not very innovative military engineer.[55] Here Leonardo's drawing style is more mature; at the same time, his recourse to classical sources and contemporary texts such as Valturius' treatise on the art of war, published in 1482[56] and used as a source of information on ancient war machines as well as on a vast range of technical terms (in the Codex Trivulzianus), becomes increasingly evident. The drawings of military engineering dating from Leonardo's first decade in Milan constitute a precise, eloquent illustration of his letter to Lodovico Sforza. The reference in that letter to "extremely light, strong bridges" is echoed in the sketches of bridges on several sheets of Paris MS. B (see, for example, f. 23 r: Fig. 56) and of the Codex Atlanticus (see f. 855 r/312 r-a: Fig. 57, which shows a strongly cambered movable bridge, easy to set up and very sturdy). In addition, we find a considerable number of studies of weapons and instruments of attack recorded in Paris MS. B and in the Codex Atlanticus on sheets dating from these years, some of which (crossbows

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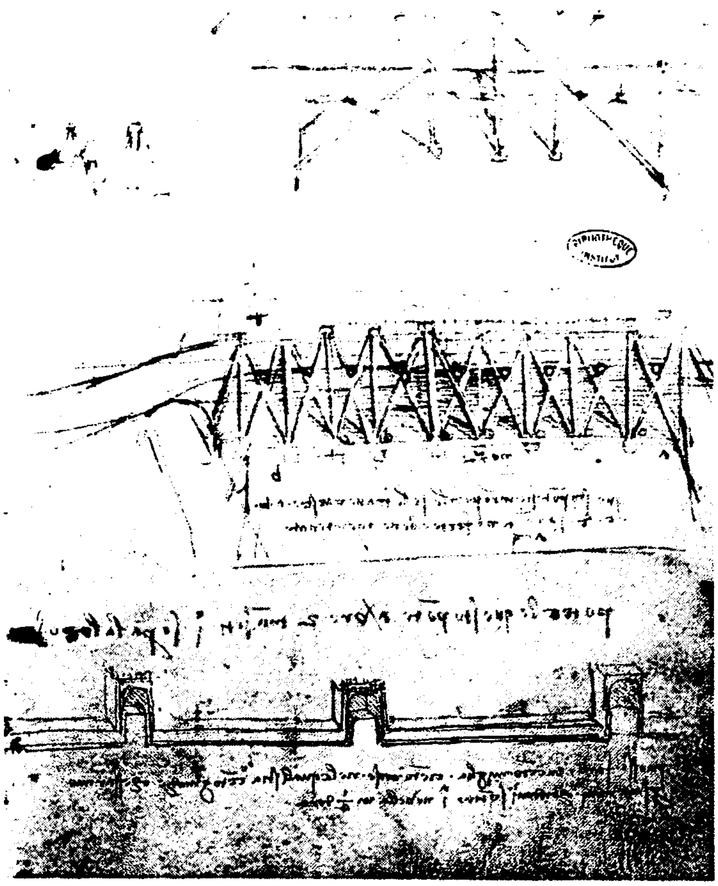


Fig. 56. Paris MS. B, f. 23 r.

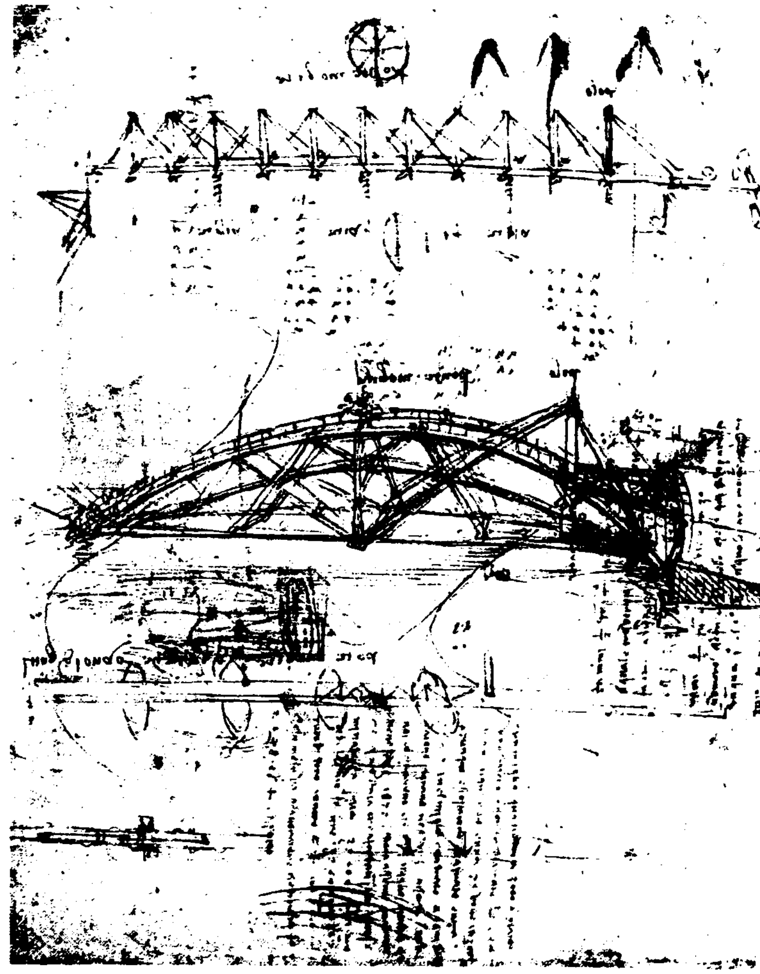
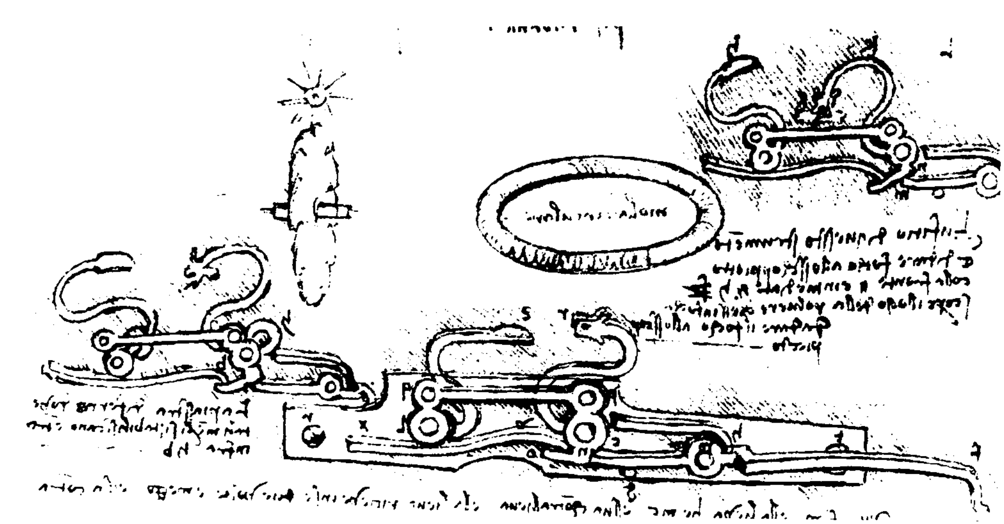


Fig. 57. CA, f. 855 r/312 r-a.

and catapults) were derived from Valturius ("I will make bombards," — Leonardo had written to Lodovico — "mortars, and light ordnance of fine and useful forms, out of the common type"). These studies are of interest not for their innovativeness, which is limited, but for the attempt they reveal to increase the firing rhythm, to facilitate the loading process even to the point of introducing automatic fuse ignition (Madrid MS. I, f. 18 v: Fig. 58), to lessen recoil, and to improve methods of rapid aiming. Leonardo's gifts as an engineer often come into play in the mechanization of operations. This is evident above all in the spectacular studies for the huge wheel operated by manpower (CA, f. 1070 r/387 r-a: Fig. 59) that permits the repeated discharging of the four powerful crossbows with which it is



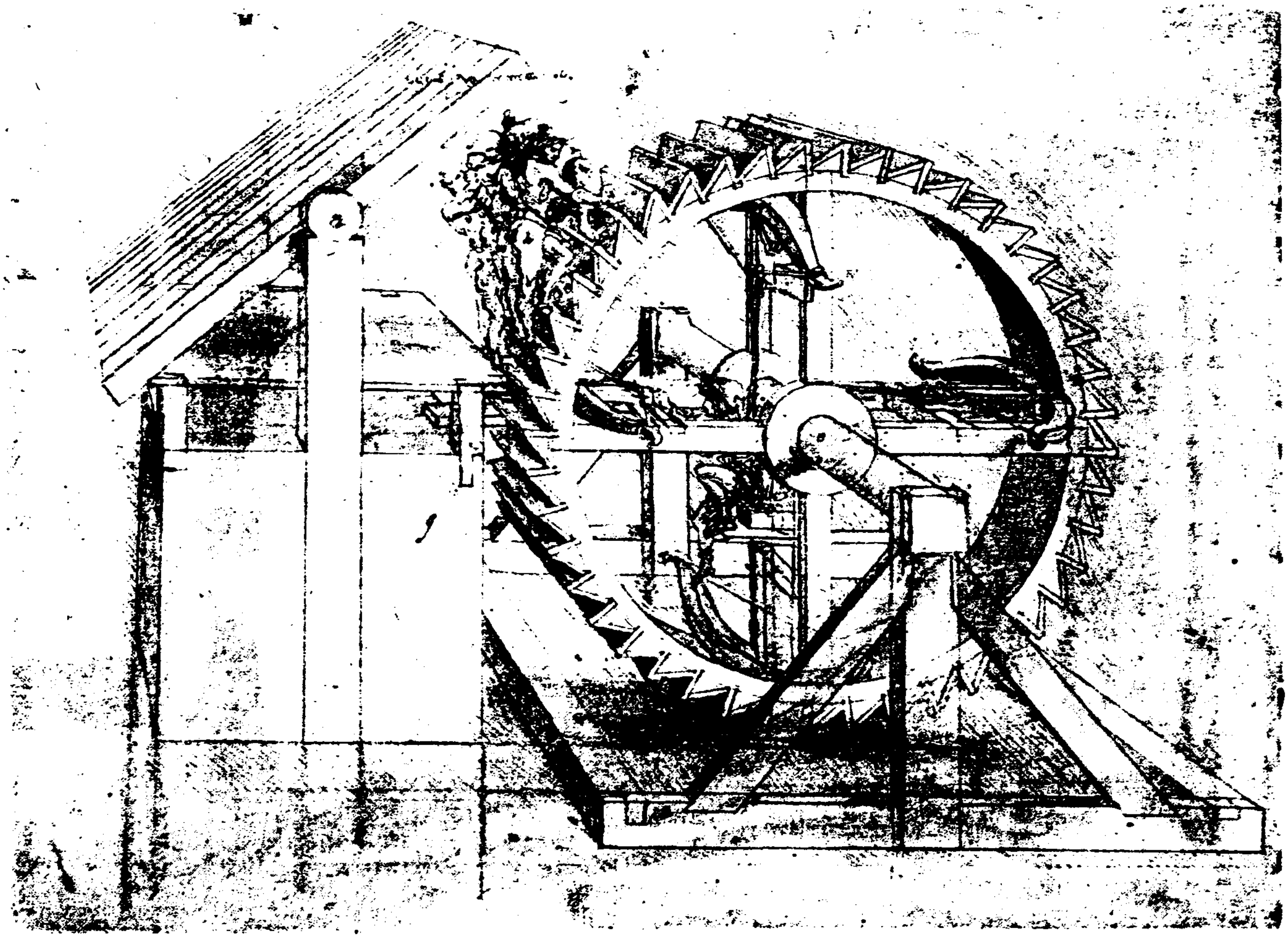
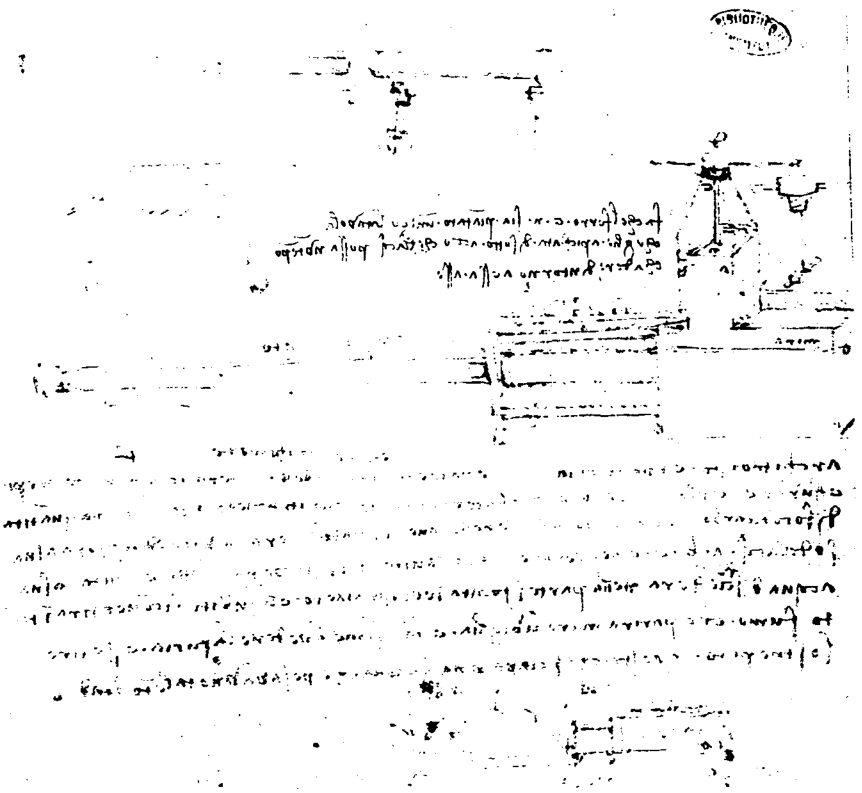


Fig. 59. CA, f. 1070 r/387 r-a.



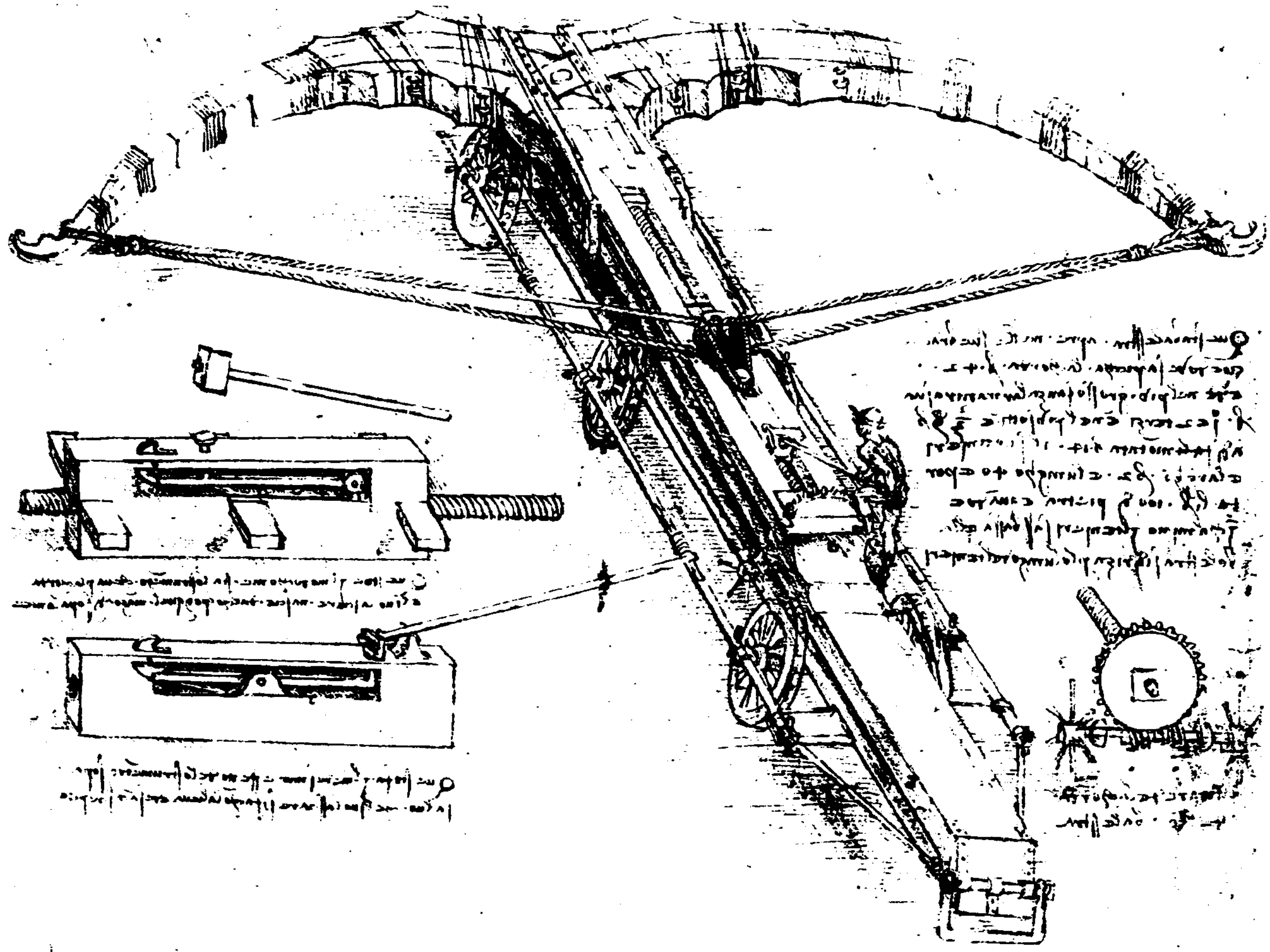
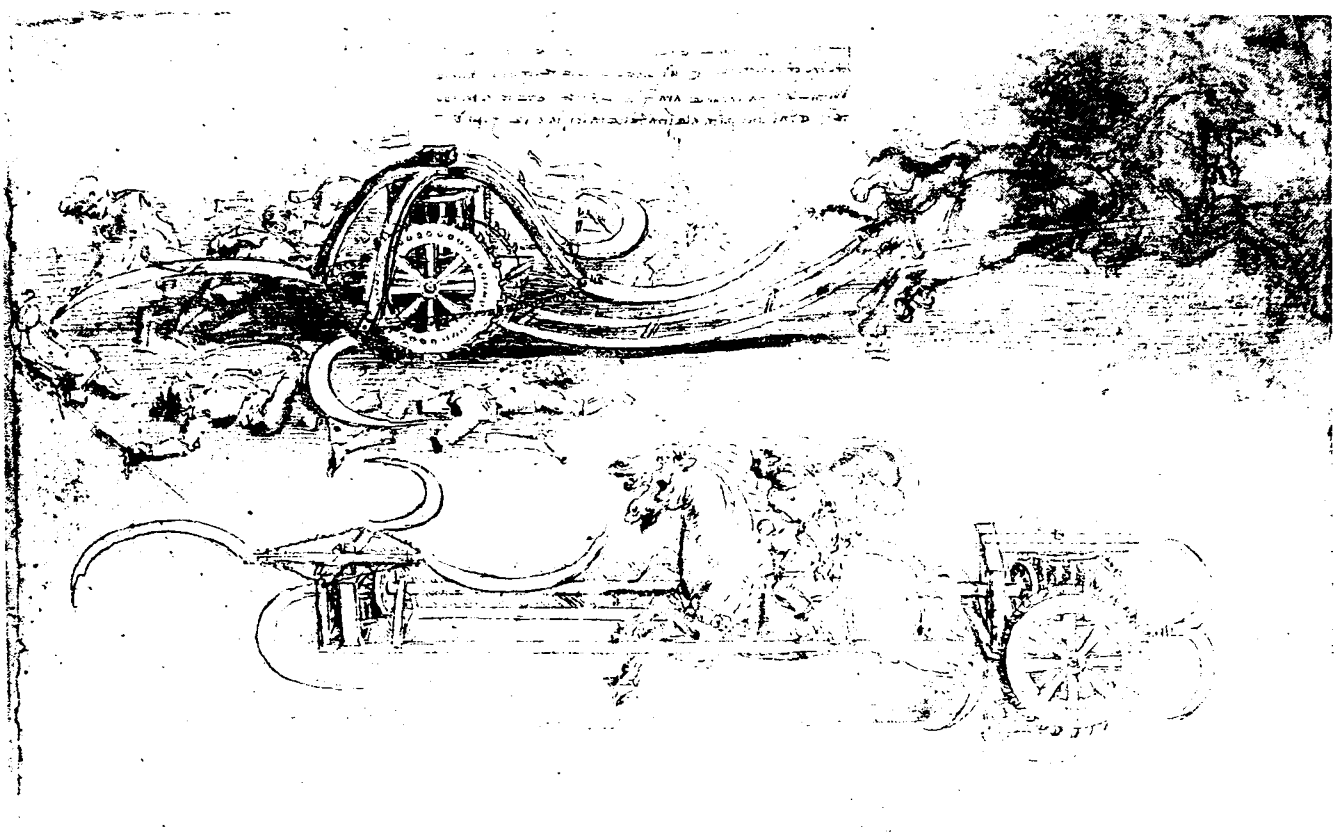


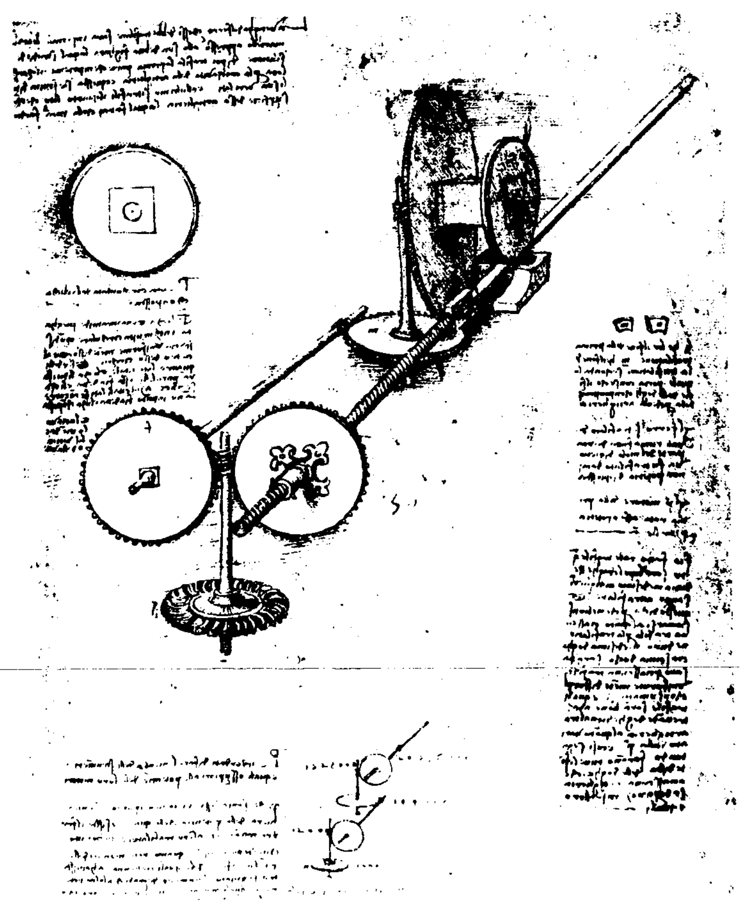
Fig. 60. CA, f. 149 Br/53 v-b.



equipped; or in the gigantic crossbow with highly technological methods of loading and activating the release (CA, f. 149 b-v/53 v-b: Fig. 60). These studies, along with the "*architronito*" in Paris MS. B (f. 33 r: Fig. 61) which Reti identified as a steampowered cannon,[57] belong to the group of Leonardo's technological "dreams" that constantly recur in his studies. Leonardo was able to create, through his highly effective, dynamic drawings, the impression that these improbable mechanisms would work. This is the case of the extremely heavy, impractical armoured car ("I will make covered chariots, safe and unattackable", Leonardo had promised Lodovico Sforza), the model of which is presented in many museums[58] as an invention of Leonardo, thereby ignoring the practically identical drawings in earlier manuscripts. The same can be said of various cars with scythes, the drawings of which (for example the beautiful drawing in the Royal Library at Turin: Fig. 62)[59] dramatically illustrate the disastrous effects produced in the enemy ranks, but which Leonardo admitted "often did no less injury to friends than to enemies" (Paris MS. B, f. 10 r).

Naturally Leonardo also occupied himself with the production of firearms, such as the hydraulic milling machine that produced segments of barrel to be successively welded together (CA, f. 10 r/2 r-a: Fig. 63) to obtain large-scale barrels for firing, like the one being raised by an excited group of workers using a powerful crane in a magnificent drawing at Windsor (RL 12647: Fig. 64), which offers a spectacular image of the chaotic, noisy activity in a cannon foundry.

As he had promised Lodovico Sforza, in the event of war at sea Leonardo could provide "many machines most efficient for attacking and defending vessels". We have already pointed out that some of Leonardo's studies of submarine warfare and devices for breathing underwater, which have been traditionally related to his brief stay in Venice in 1500, are unquestionably from his early years in Milan.



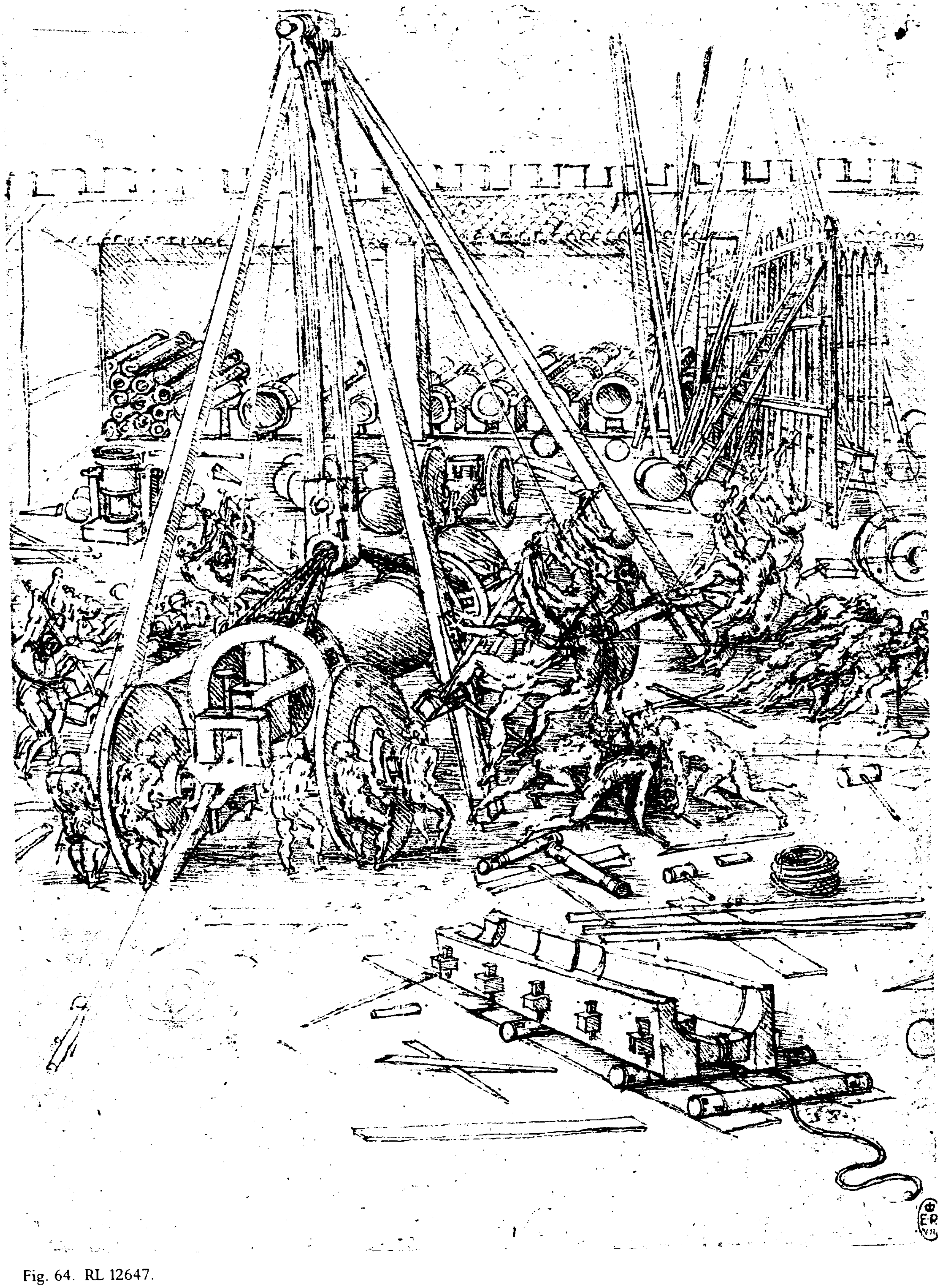
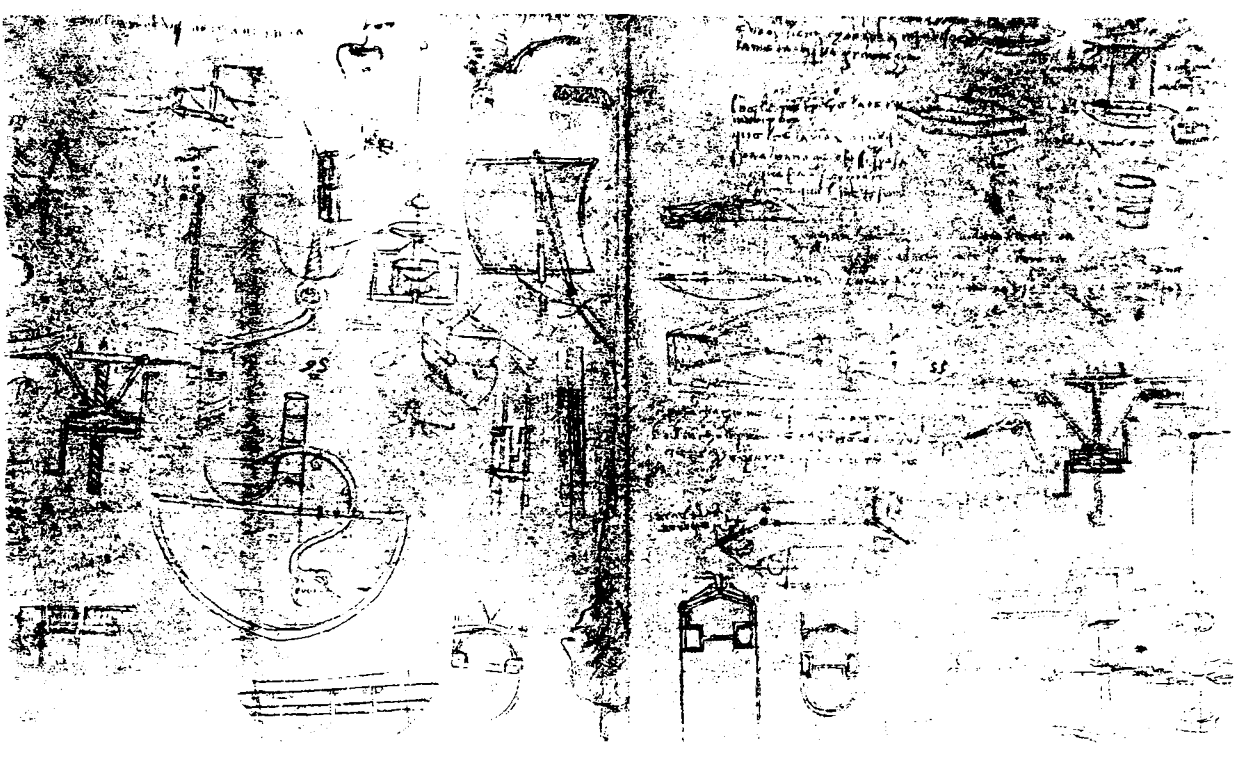


Fig. 64. RL 12647.

These studies were probably inspired by Lodovico Sforza's intention of defending Genoa, which came under his dominion in 1487, from continual pirate raids. On a sheet of the Codex Atlanticus (f. 881 r/ 320 v-b: Fig. 65), along with various interesting but not new devices for breathing underwater, we find sketches and notes that seem to be evidence of a project for an underwater vessel, "Leonardo's submarine", as it was quickly baptized by traditional scholarship. But the evidence is sparse and does not permit a precise reconstruction of Leonardo's project. Carlo Pedretti, interpreting the drawings and various references to this vessel scattered throughout Leonardo's papers (see especially Paris MS. B, f. 11r), has conjectured that Leonardo was thinking of immersing a hermetically sealed, completely watertight vessel by releasing the air from the leather bags placed along its sides to keep it afloat.[60] This is probably another of Leonardo's technological dreams, founded upon the development of a chain of daring ideas which led him to materialize, in his imagination and on paper, projects that were beyond the possibilities of the technology of his time. But these great possibilities produced by his vivid imagination also troubled Leonardo. In a later note he stated that he had destroyed this invention to prevent "the evil nature of men" from transforming it into an instrument of death by using it to make unseen attacks on enemy ships (Codex Hammer, f. 22 v).

It has often been stressed that Leonardo felt repugnance for war. And in fact his studies of military technology do not reflect a genuine interest on his part, even though he was fascinated by certain technical details. Such studies were the result of his obligations to lords, like Lodovico Sforza, who saw war as the chief means of defending and increasing their power.

Leonardo's activity as a hydraulic engineer during his first Milanese period was characterized by elements of uncertainty. The once widespread tendency of Leonardo scholars to attribute to him a fundamental role in the definition of the extensive canalization works in Milan at the end of the fifteenth century is less common today. There is no lack of documentation attesting to his involvement in works of hydraulic engineering; and it is not surprising that Lodovico Sforza required Leonardo's services in this field. And yet one has the impression that Leonardo experienced difficulties at the



beginning of his activity in this area. In fact, his knowledge was based on his experience with the problems presented by a capricious, unpredictable river like the Arno. He lacked the necessary tools and experience for dealing efficiently with a complex system composed of rivers of constant flow (the Adda and the Ticino), numerous tributaries, lakes, and canals which were to be used as a network of communication and for the transportation of goods to a city — Milan — that was distant from the main waterways. When Leonardo arrived in Milan the structure of the Milanese canals had already been determined to a great extent. The Martesana canal, constructed by Bertola di Novate, made it possible to link Lake Como and Milan by means of the Adda River. Another network of canals connected, via the Naviglio Grande, the city of Milan to the Ticino River, on the banks of which there rose Pavia — the second most important city in the duchy of Milan — with its famous Studio.[61] Leonardo's attention was caught by many of the technical solutions used in the great projects: basins, systems of locks, dredges to keep the canals clean, adjustable apertures in the banks of the canals to supply water, and so on. Understandably, one of Leonardo's main concerns seems to have been to orient himself within this complex system. In fact, there is evidence of his efforts to grasp the main coordinates of this unfamiliar territory by making personal expeditions, taking measurements, and drawing up schematic maps. Obviously, he concentrated on the navigable network; there is evidence of this in the sketch of the map of Milan with indications of a project for replanning the area between Porta Romana and Porta Tosa, which can be dated 1493 (CA, f. 184 v/65 v-b: Fig. 66). One of the tasks given to Leonardo by Lodovico Sforza at the beginning of the 1490s was to draw a plan for the enlargement of the city of Milan, reviving the mediaeval structure of the city by exploiting to the full the advantages offered by the abundance of water.[62].

In 1490 Leonardo went to Pavia in connection with a project to build the Cathedral. There are traces of his observations of the Ticino River, in particular of the way to reinforce the foundations of the city walls, against which the river flowed. And he was certainly fascinated by the multiple locks of the Naviglio Bereguardo. Leonardo's first drawings of locks in the Codex Atlanticus (f. 935 r/341 v-b:

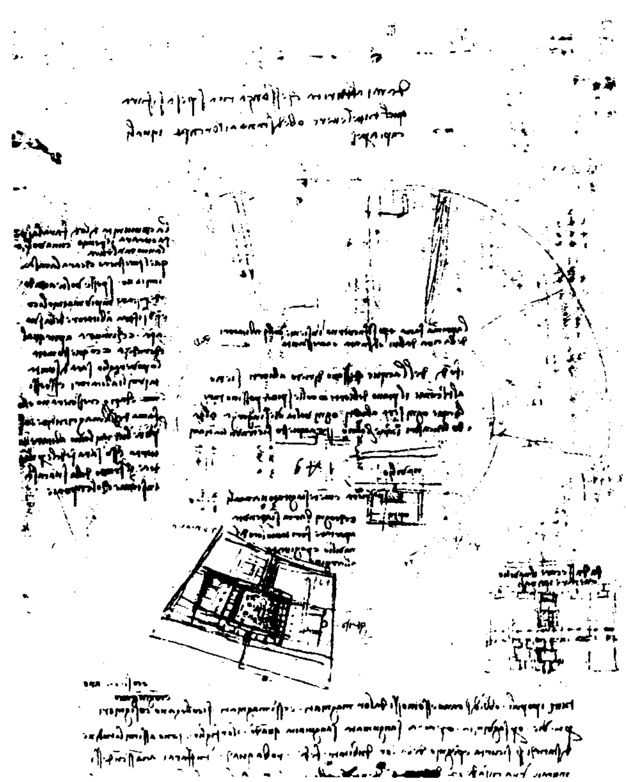


Fig. 67) and in Paris MS. B (f. 64 r: see Fig. 39) may have been inspired by this visit to Pavia, or possibly by another earlier visit around 1487–8, and may reflect an original project for a movable lock to regulate the flow of water in canals. In Pavia, where navigation from Milan to the Ticino was interrupted by the insurmountable obstacle of the fluvial terrace, Leonardo must certainly have begun to reflect on a solution to that extremely bothersome barrier.[63]

Leonardo's manuscripts from the early 1490s show that his interest in hydraulic technology was unflagging; there are numerous references to canals and to Milanese localities linked by the system of waterways. And he continually referred to problems that were yet to be satisfactorily overcome: how to keep a constant level of water in the canals; how to design high-capacity locks (like the ones with their gates at an angle); how to operate effective devices for supplying precise quantities of water from the apertures in the banks of the canals (an important problem, since the water supply granted by Lodovico Sforza was based upon a payment "per ounce"). It is more difficult to establish the extent to which this impressive series of drawings and notes represents original ideas, or is simply a matter of Leonardo recording work he saw in progress. It seems that for a considerable period of time Leonardo was more involved in learning than in teaching in this field. He sought contacts with Lombard experts in hydraulics, of whom he had a thousand questions to ask: "find a master in waterworks, and get him to explain to you the fortification of them, and what it costs"; "Paolino Scarpellino, called Assiolo, is a good master of waterworks". These notes, from a memorandum of 1489 (CA, f. 611 Ar/225 r-b), provide solid evidence of a new period of training to which Leonardo dedicated himself passionately.

But while he was striving to learn from the experience of those who were well versed in hydraulics, Leonardo was developing a highly personal method, which becomes increasingly evident in his papers. Between the end of the 1480s and the beginning of the 1490s, in fact, Leonardo's career as an engineer took a decisive turn — a turn that was determined by his studies of hydraulics and that led him to change his method. He became convinced that experience could help him only up to a certain point. The problems posed by flowing rivers, canals, locks, and those of providing a water supply for domestic and agricultural uses, demanded that the engineer be well acquainted with the element water before he could succeed in turning it, with the proper mechanical instruments, to the use of man. Leonardo's first "theoretical" studies, of which water was most frequently the object, date from these years. "A grandson of the painter Gian Angelo has a book on water that belonged to his father", we read in the memorandum of 1489 cited above. Paris MS. A, of 1490–1492, contains the first relatively comprehensive prospectus of Leonardo's study of water: "beginning of the treatise on water".[64] This is a fundamental statement, the first to document Leonardo's intention of dedicating himself to the compilation of a "treatise". And the fact that it was to be not merely a collection of practical precepts but a comprehensive text is also clear from Leonardo's stated intention of returning to and further developing what the ancients had written on the subject. This was a very ambitious project. In Leonardo's fertile brain it already appeared as the principal section of a vast encyclopaedia destined to contain other closely related chapters: on motion and weight, on human anatomy, on the earth. For Leonardo, water is a universal factor: it carves out valleys, it circulates in the bowels of the earth giving rise to springs, it flows as blood through the human body, and everywhere its incessant movement is subject to ironclad laws. It is not by chance that Leonardo's very first mention of a treatise on water in Paris MS. A contains a specific reference to the similarity between the human body and the earth: "Man has been called by the ancients a lesser world, and indeed the term is rightly applied, since, as man is composed of earth, water, air, and fire, this body of the earth is similar".

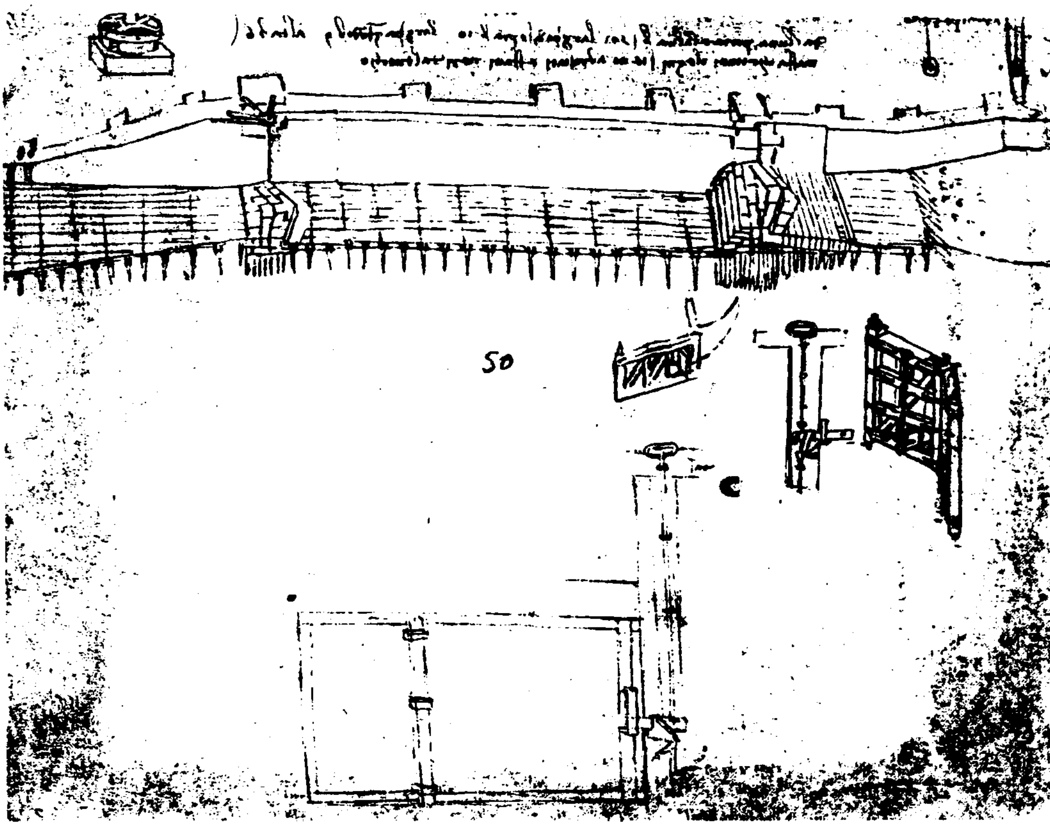


Fig. 67. CA, f. 935 r/341 v-b.

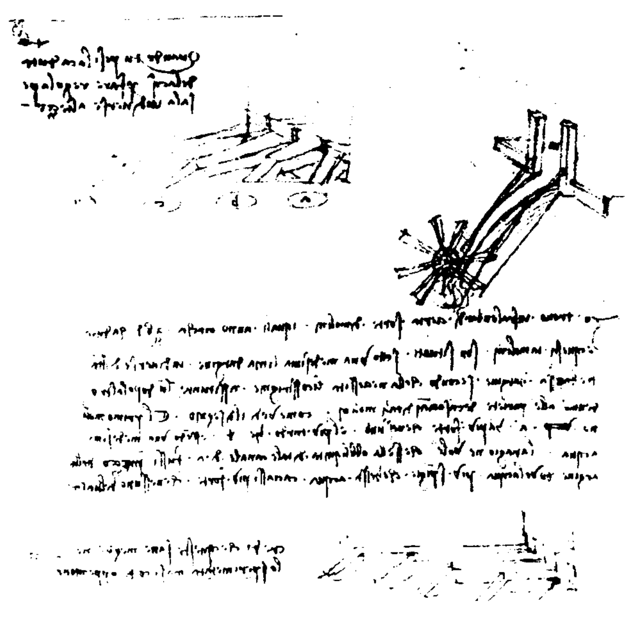
Hence Leonardo saw a unity between the animate and the inanimate worlds — and consequently he believed in the validity of a rigorously mechanical investigation of man. As a result he conducted a series of systematic dissections that began during the years under consideration, constantly insisting upon the relationship between man and the earth (respiration, circulation of humours, and so on) — a recurring analogy the main component of which was the element of water.

During these same years, because Leonardo was also an artist who strove to achieve a perfect imitation of Nature (which is impossible without a precise knowledge of its laws), he began his theoretical studies of optics and mechanics. The latter are found above all in the Codex Atlanticus, in Madrid MS. I, and Forster MSS. I², II¹⁻², and III. The pattern is the same: Leonardo studied classical and mediaeval sources (there is evidence of his search for important texts: Archimedes, works on the mediaeval science of weights and the texts of the *impetus* theory); he would then establish useful contacts with experts of his time (the Marlianis,[65] Fazio Cardano,[66] etc.); and, finally, he would attempt to establish the general mechanical principles involved, testing them in concrete applications. Leonardo soon discovered that the basic unifying tool for these studies was geometry, of which he was totally ignorant. So he enthusiastically dedicated himself to filling this gap in his knowledge. The first signs are found in a memorandum of 1489, and show Leonardo's usual method of searching for texts and seeking out experts in the field: "Get Messer Fazio [Cardano, the father of Gerolamo] to show you about proportionality"; "Get the master of arithmetic to show you how to square a triangle"; "the proportions of Alchino [Al Kindi], with Marliani's notes; Messer Fazio has it"; and "Try to get Vitolone [Witelo], which is in the library at Pavia, and which treats of mathematics". Moreover, in 1497, Leonardo had the good fortune to meet Luca Pacioli, one of the many Tuscans attracted by the Sforza court, who became his great friend and from whom he received a course of geometrical instruction based on Euclid's *Elements*.[67]

It is not possible to dwell further on this remarkable turning point in Leonardo's career, which was to have direct, striking repercussions on his activity as an engineer. By the middle of the 1490s, Leonardo had already outlined his theory of the four "*potenze*" of Nature (movement, weight, force, and percussion), the four basic powers upon which every physical phenomenon depends. And already at this time, air and water, which Leonardo was to increasingly associate with one another (influenced also by his study of the flight of birds), are presented as powerful natural forces in perennial motion that man can harness and turn to his own benefit.[68]

And yet there remain obvious contradictions — which never disappear — between Leonardo's ambitious programmatic declarations and the concrete development of his observations and comments, which unfolds in a fragmentary fashion, by "cases". The studies in Paris MS. A, after the formulation of a project as ambitious as the treatise on water, are quite disappointing (the same can be said of the later Paris MS. I, *c.* 1497, which deals with the same problems). Leonardo focused his attention primarily on water courses. He attempted to determine the variation of the velocity of their various levels in relation to the variations in the breadth and depth of the bed and the velocity of the current. He also studied the effects of the impact of water on bodies immersed in it and on the edges of the bank.[69] On the one hand Leonardo outlined the contents of ambitious theoretical works as if they had already been written; on the other hand, he continued to conceive his own studies as a series of disconnected observations.

Although Leonardo never actually compiled the *summae*, as he so often solemnly promised, his efforts to base practical applications on general principles led to considerable changes in his technological activities. The first evidence of this change is found in a series of drawings and notes from 1494 relating to hydraulic projects. In that year Leonardo was at Vigevano, the birthplace of Lodovico Sforza and the setting for ambitious Sforza projects. Leonardo's notebooks from this time contain various observations on the canals of the town and on the water stairs used at the Sforzesca, Lodovico's model farm, to keep the sloping meadows green. Among the many pages that refer to this visit in Madrid MS. I, which was compiled between 1492 and 1499, and in Paris MS. H, from the same years, those dedicated to the mills at Vigevano are of particular interest.[70] Leonardo took precise measurements of the grain mills he observed; he calculated the cost of building one, estimating its daily production capacity (Madrid MS. I, f. 151 v: Fig. 68). Moreover, he thought about the



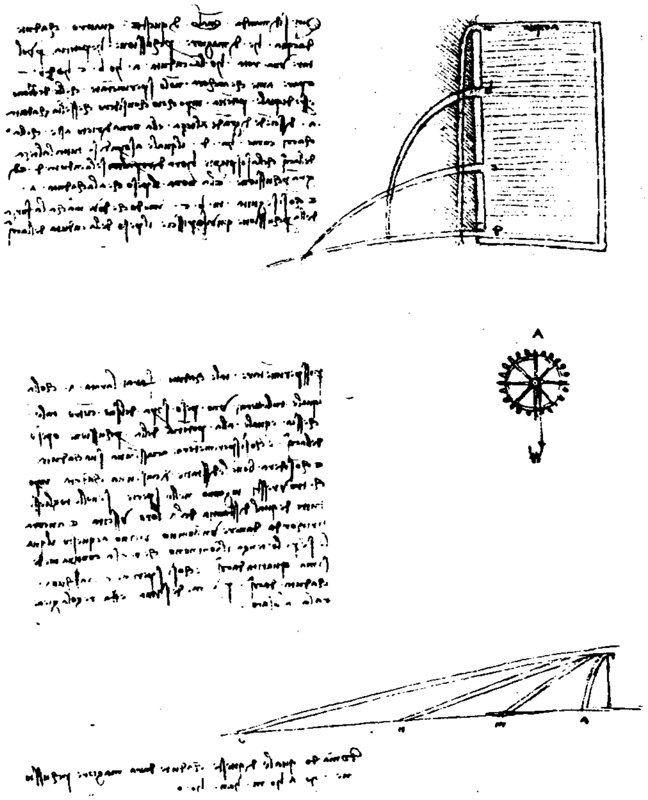


Fig. 69. Madrid MS. I, f. 134 v.

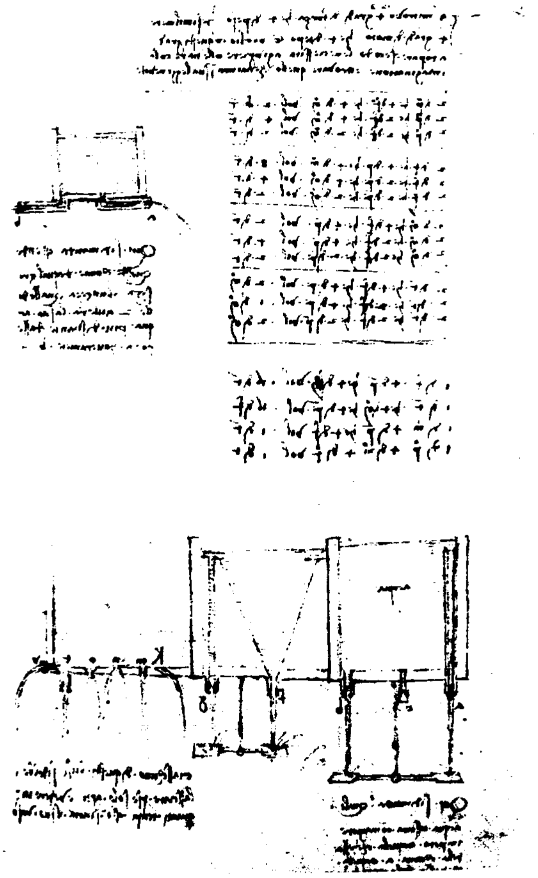


Fig. 70. Madrid MS. I, f. 152 r.

deficiencies of the mills in Lombardy ("I found among the Lombards a certain type of mill..."), and he proposed solutions which, albeit confusedly, were obviously based upon principles of hydrostatics and hydrodynamics. Leonardo criticized the solution he had observed at Vigevano where various mills were placed in a line along the same bank and their blades powered by jets of water coming from spouts of uneven diameter (wider where the water entered) at different angles from the flow of water from which they drew. In this case, Leonardo observes, recalling his studies of currents and the flow of rivers, the output of the mills cannot be uniform. To make it so, he proposes to divert from the water course horizontal ducts of uniform diameter.

Elsewhere in Madrid MS. I (ff. 134 v and 152 r: Figs 69-70), Leonardo investigates the causes that make a fall of water more or less effective, experimentally analyzing the effect of four falls of water from four equal openings made at different heights in a container full of water. His analysis depends on a theoretical argument based upon the conviction that the power of the jet of water is a result of the combined effect of the weight of the water and of its percussion, where the percussion, by virtue of its *impetus*, is proportional to the height from which the water falls. Leonardo concludes that the four falls "should be of equal power". He notes that "where the force of percussion is lacking, the weight compensates", taking for granted that the power of the lower and upper jets is equal because the former has more weight (due to the pressure of the water above it) and less percussion (since it falls from a lower height), while the latter has more percussion and less weight.

These notes are telling evidence of a change in method consequent upon the appearance in Leonardo's manuscripts of a theoretical approach not yet quantitatively oriented, but no less important for that. These studies opened up new perspectives for Leonardo as an engineer, enabling him to design mills with a better output and to calculate the flow of water from the mouths of canals in relation to the height of the opening. It is not accidental that in both studies in Madrid MS. I relating to mills, Leonardo advances his proposals solely on the basis of theoretical previsions, stating explicitly that he has not tested them: "And it seems to me, although I have not yet tested it, that they should be of equal power"; and again, "I believe that these will be better. I have not tested it, but I believe so". What we have here are truly "thought experiments": Leonardo's faith in the theoretical foundations from which the foreseen effects derived made experimental verification perfectly useless.

This was the fruit of a major change which appears clearly in several technological studies by Leonardo from the late 1400s and early 1500s. Nevertheless, Leonardo's practical applications never came to depend totally on his theoretical knowledge; his manuscripts up to the time of his death contain a remarkable number of specific technical projects, isolated cases in a world of mechanical possibilities, each one of which apparently possessed its own individuality. In spite of this contrast, however, at this point in his career Leonardo showed himself quite different from other engineers of his day, who also operated by "cases". The "disciple of experience" was immersed in the study of mathematics, of the mechanics of solids and liquids, of geology. He was striving to enrich and refine his vocabulary, to perfect his knowledge of Latin, and to measure up to the great minds of the past.

Hence the last decade of Leonardo's first Milanese period marks a decisive turn in his career, a turning point that is particularly evident in the series of studies in Madrid MS. I. These studies constitute the most significant example of Leonardo's efforts to combine theoretical foundations with practical applications, using mechanical principles as his point of departure. We will return later to this aspect of Leonardo's activity in order to subject it to a special analysis, imposed by its centrality, and also to clarify the approach, based largely upon theoretical studies of mechanics, which Leonardo took toward human anatomy during these years.

Alongside these signs of innovation, there are other technological studies from the last years of Leonardo's first Milanese period which retain the traditional character of ingenious solutions to special problems, based on practical experience. This is the case of the series of studies for the casting of the gigantic horse (almost seven metres high) for the equestrian monument to Francesco Sforza commissioned from Leonardo by Lodovico il Moro (Fig. 71). The various solutions recorded in the magnificent red-chalk drawings in Madrid MS. II[71] for transporting the form and turning it in the casting pit, and pouring the molten bronze, are truly remarkable (Figs 72-73). But Leonardo was unable to test their efficacy because the enormous amount of bronze necessary for the process went to Ercole d'Este for military purposes.[72]

Also characteristic of Leonardo's habitual method of analysis is the series of drawings, all dating from the last five years of the fifteenth century, which present various machines and devices for the textile industry with remarkable visual effectiveness. We should make clear, however, that there is no concrete proof that Leonardo was the inventor of the automatic spinning machine, the loom (Fig. 74), the cloth shearing machine (Fig. 75), the gig mill (Fig. 76), and so on, as has been suggested by Giovanni Strobino in what remains a useful study for the technical knowledge with which Strobino reconstructs the way that the devices sketched by Leonardo must have operated.[73] While living in a region where there was an extremely active textile industry, the technology of which we know almost nothing about, it is likely that Leonardo recorded the most advanced solutions then available, perhaps taking as his point of departure the functional deficiencies about which the people who operated the

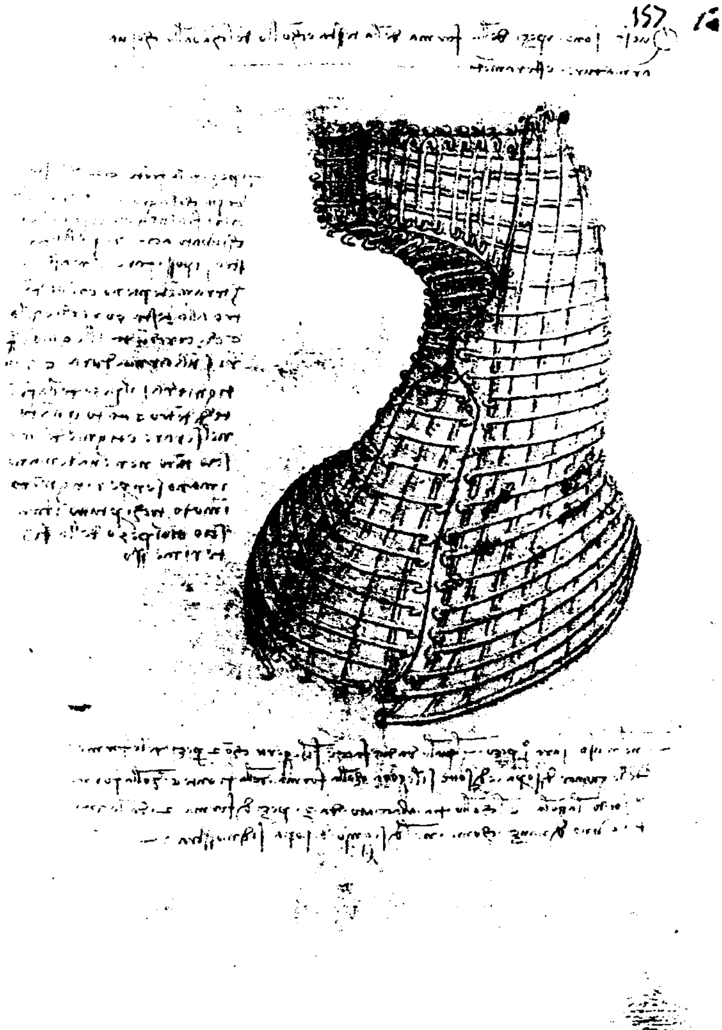
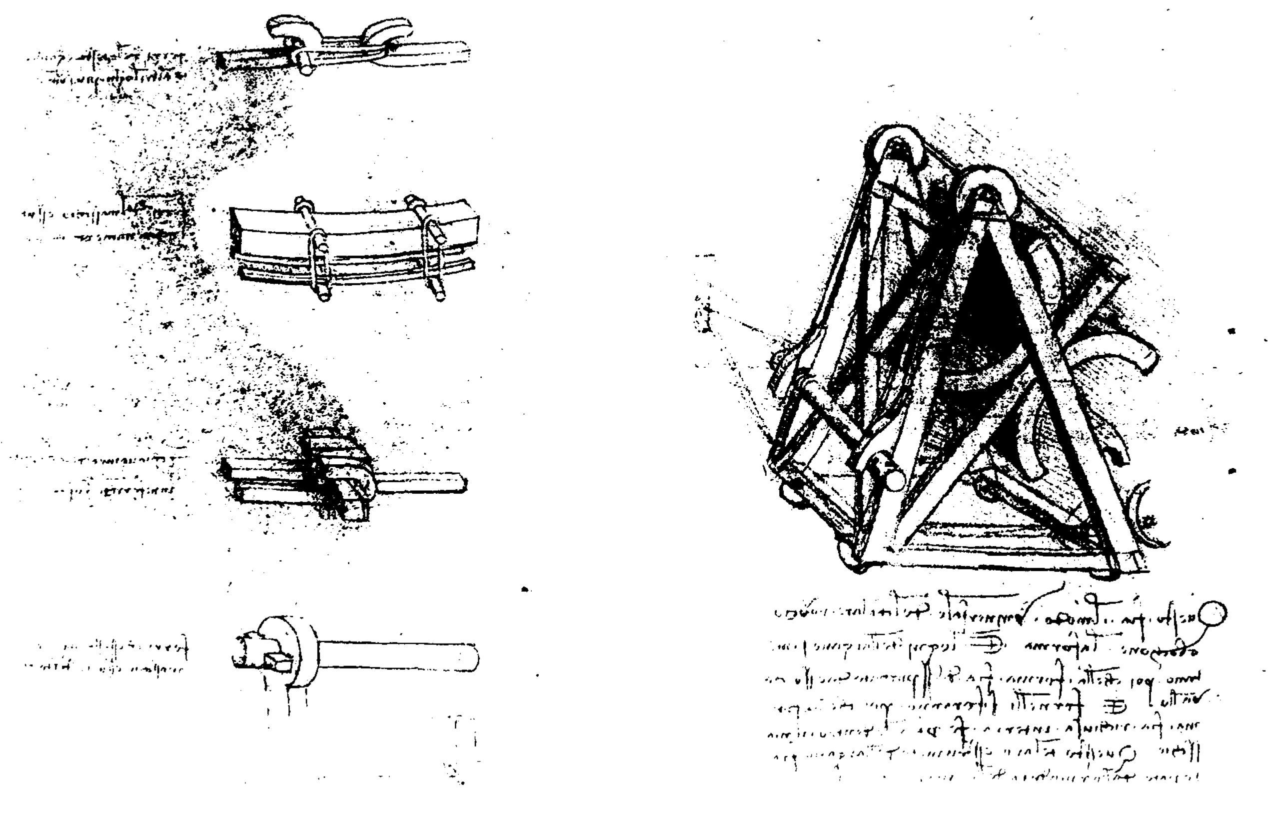


Fig. 71. Madrid MS. II, f. 157 r. The casting mould of the Sforza horse's head.



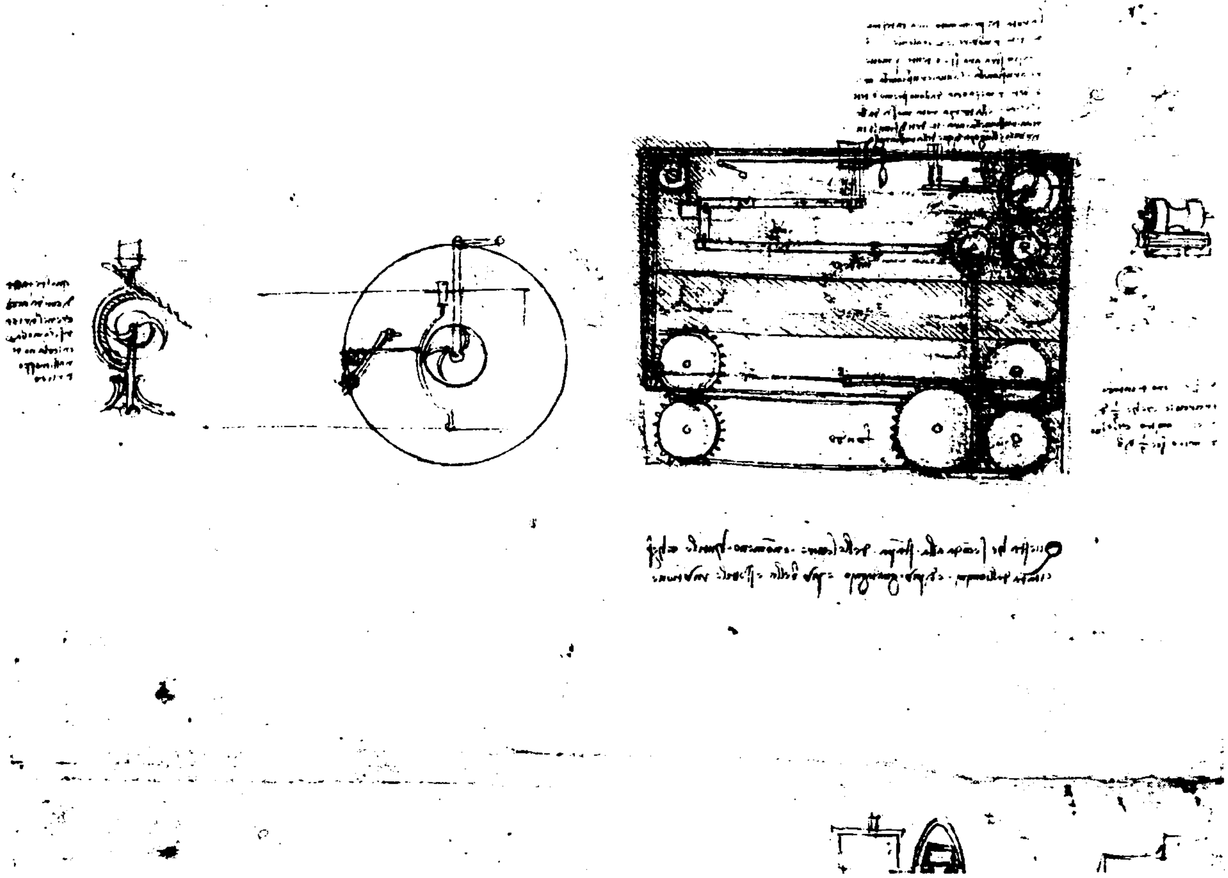
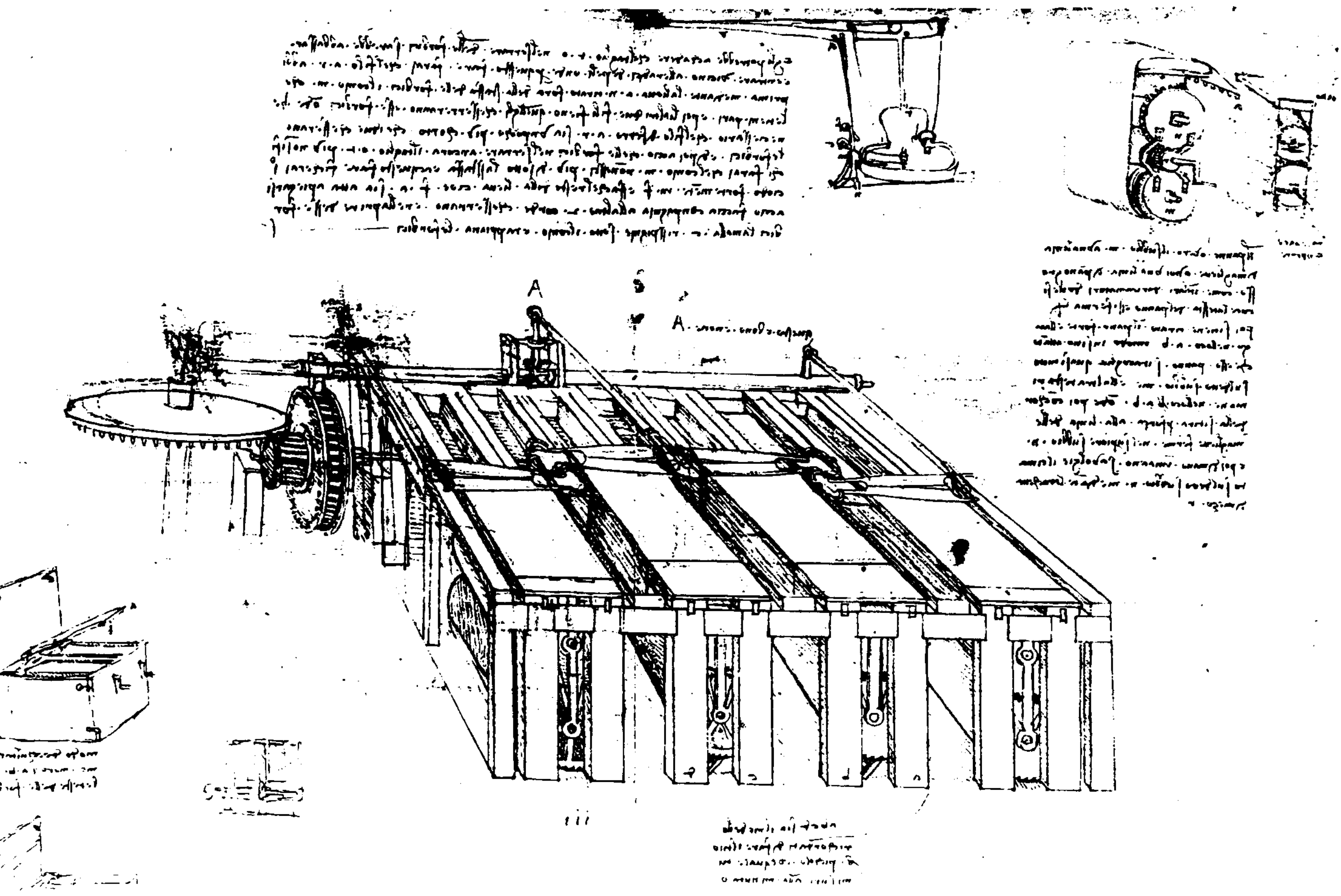
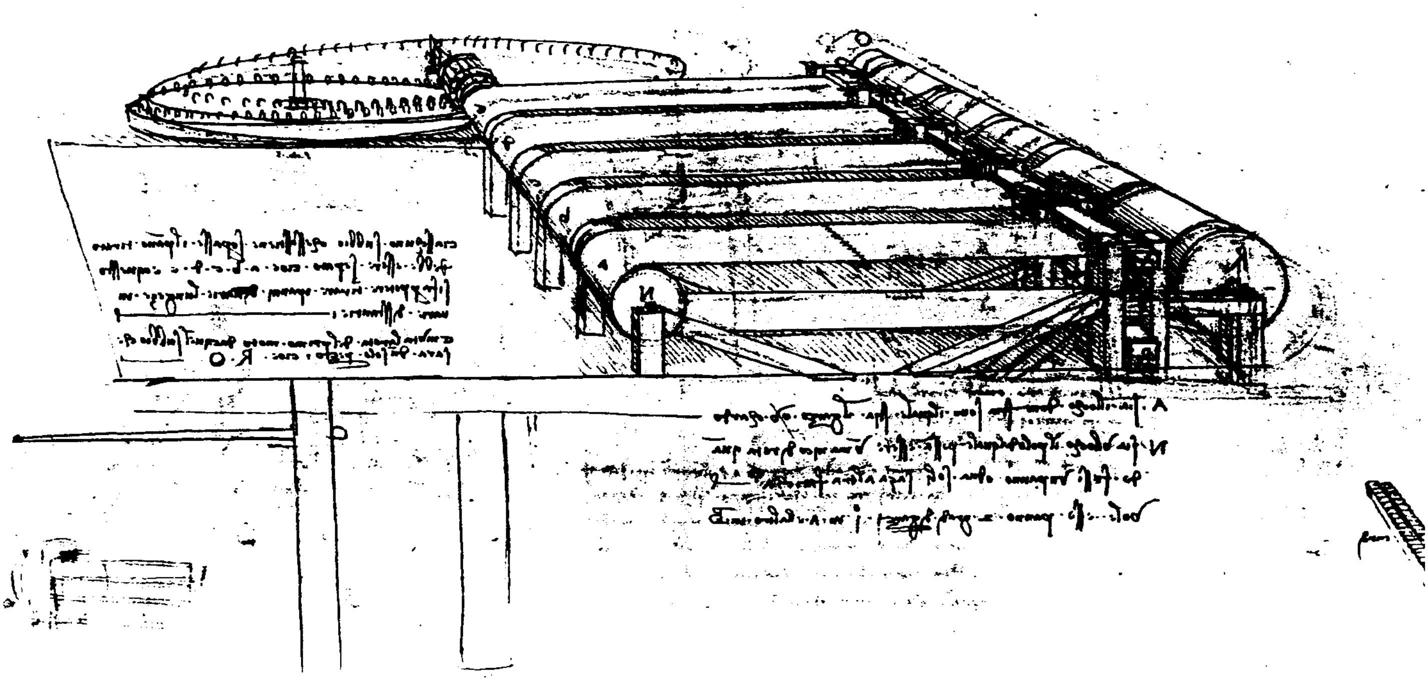


Fig. 74. CA, f. 985 r/356 r-a (detail).



machinery complained, in order to propose his own solutions. As a whole, this series of projects represents an attempt to automate the production cycle, from which Leonardo could reasonably expect to derive great financial advantage: "this is second" — wrote Leonardo beside the drawing of the mechanical loom — "to the letterpress machine, no less useful, and as practiced by men it is of more profit and is a more useful and subtle invention" (CA, f. 85 r/356 r-a). The need for automation is a constant feature in Leonardo's designs of machines, and he has been rightly called the "prophet of automation".[74] But he often filled that need with the help of his imagination and the extraordinary persuasiveness of his technological drawings. Powerful machines capable of producing an enormous amount of work, such as the mechanical shearing machine (CA, f. 1105 r/397 r-a: Fig. 75), could be conceived by Leonardo's lucid mind, but they were difficult to realize because of the precision of assembly and the solidity of materials they required.

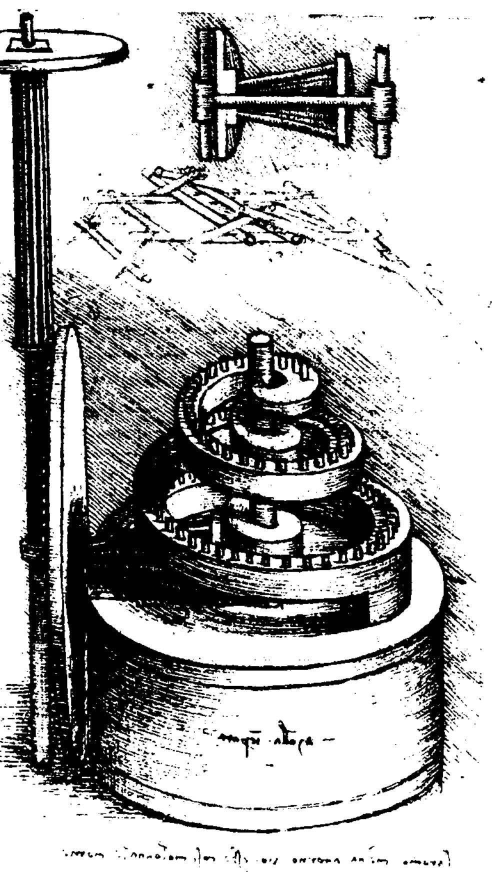
The same type of consideration can be repeated with regard to the many magnificent studies of mechanical clocks in Madrid MS. I. In fact, in a recent, very acute study of these sheets, Silvio Bedini maintained that they are works of astonishing accuracy.[75] But, with the problematic exception of Leonardo's attempts to introduce the escapement of the pendulum to regulate a weight-driven clock (Fig. 78) these studies cannot be considered sensational anticipations of modern inventions. The precision technology of the watch led Leonardo, whose attention was focused on systems of transmission and regulation of movement (Fig. 77), to a new exercise in automation. Moreover, it is not certain that all of these studies are related to clock mechanisms. We should not forget that clocks and automatons (i.e. machines capable of carrying out a series of predetermined movements) were



devices usually produced by the same technician. We also know that Leonardo devised automatons for festivals at the Sforza court and that later (1515) he produced a mechanical lion for the Florentine Republic.[76]

Before concluding this summary of Leonardo's activity as an engineer during his first Milanese period, we should mention his study of flight. As has recently been demonstrated, Leonardo had already begun to study flight during his years in Florence;[77] in Milan these studies underwent remarkable progress as can be seen in many pages of Paris MS. B (Fig. 79) and of the Codex Atlanticus which contain projects for flying machines — Leonardo's "airplanes" (Fig. 80). Raffaele Giacomelli has shown that in his early studies Leonardo concentrated on machines with movable wings.[78] And he illustrated various types of them in Paris MS. B. In some the man is prone and moves the wings with his arms; in others, the lower limbs of the man provide the thrust, or else the man is in a standing position and moves all four of his limbs (Fig. 81). These are fascinating designs which seem to have led Leonardo to believe that it was not impossible for such machines to work. There is evidence of an apparently unsuccessful attempt at human flight from the roof of the Sforza Palace (CA, f. 1106 v/361 v-b), and the subsequent choice of a less perilous location: "You will try this machine over a lake, and wear a long wineskin around your waist, so that if you should fall you will not drown" (Paris MS. B, f. 74 v).

The flying machines designed by Leonardo during these years have beating wings with extremely complicated devices for operating them. Leonardo also considered using springs continually rewound during flight. He seemed to concentrate on mechanical systems for advantageously transmitting the force exerted by the man and for transforming the constant thrust of the motor into an alternating motion like that of beating wings (Fig. 82 and Pl. IX). These are powerful and heavy machines



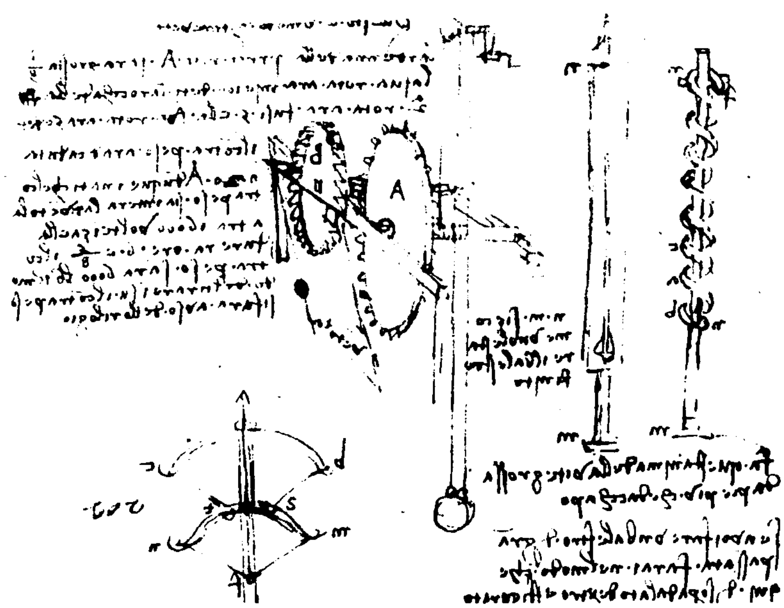
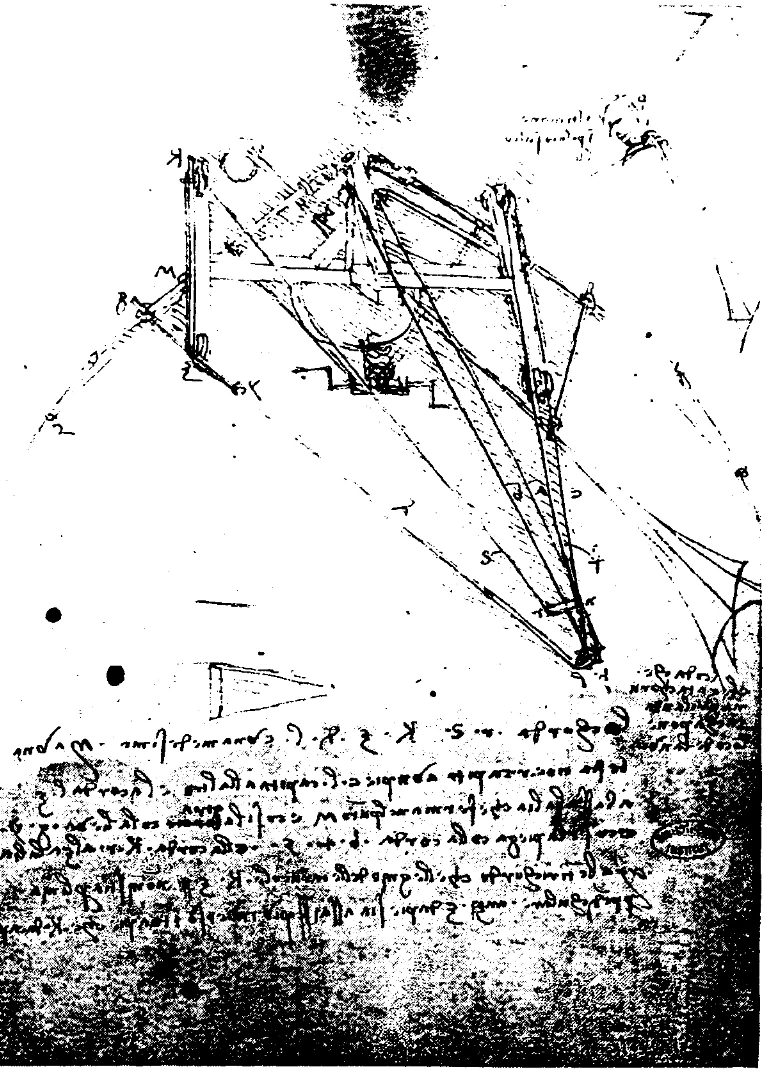


Fig. 78. CA, f. 754 r/278 r-b (detail). Study of pendulum escapement.



ig. 79. Paris, MS. B, f. 75 r.

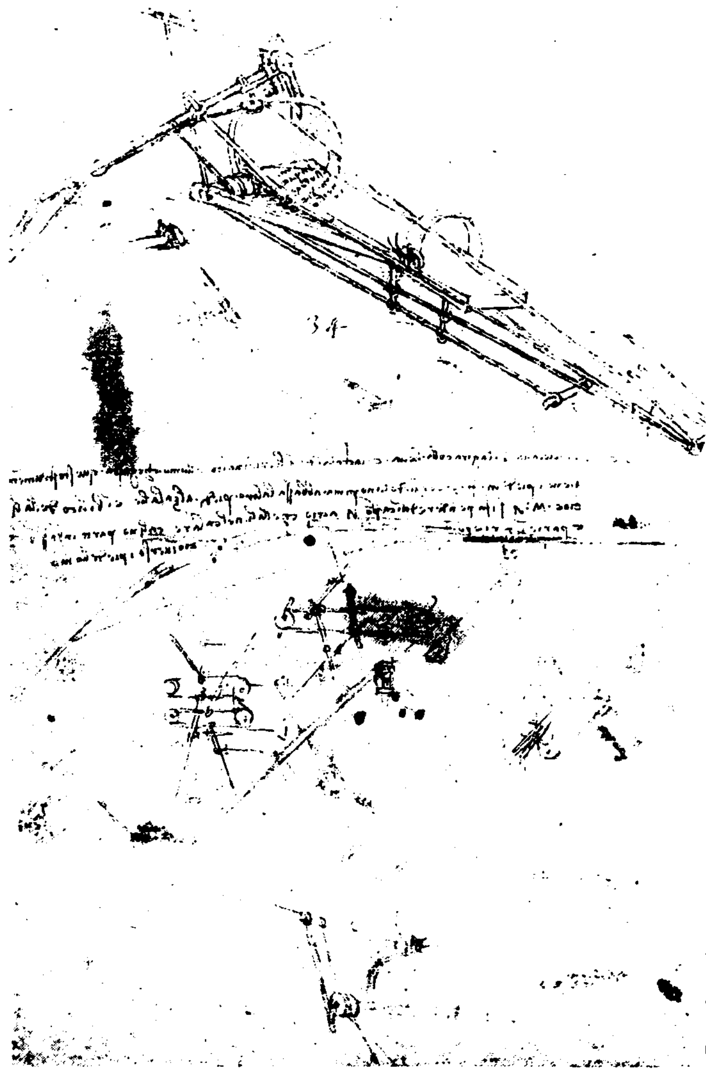
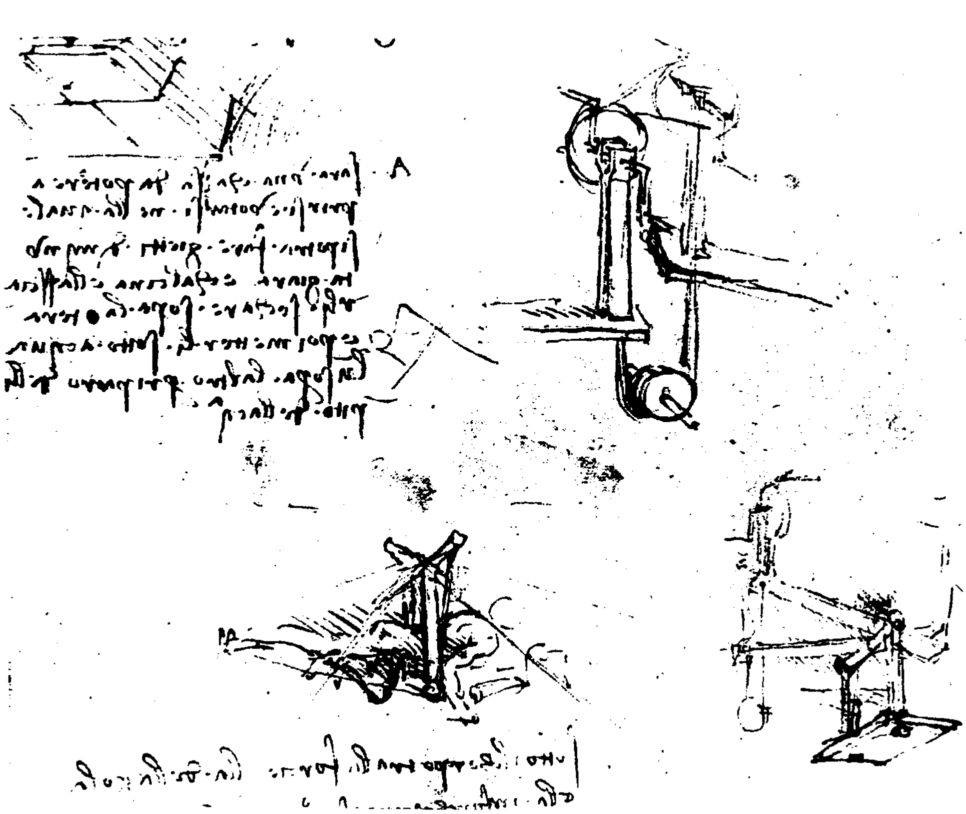
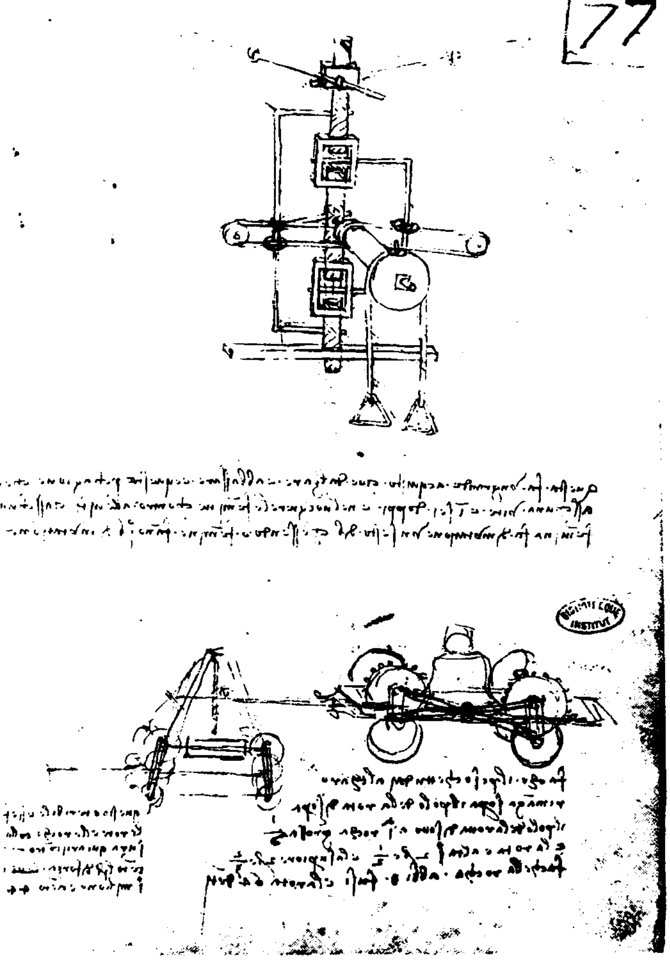


Fig. 80. CA, f. 824 v/302 v-a.





. 82. Paris MS. B, f. 77 r.

Fig. 83. Paris MS. B, f. 89 r.

to which, in the not unlikely event of a fall, Leonardo attached ridiculous shock absorbers (Fig. 83). It seems impossible that he could really have believed that a man could fly with one of these devices. And yet all the evidence indicates that for several years he worked feverishly and with great expectations on this project. The study of the anatomy of birds, which Leonardo undertook with great meticulousness, convinced him that man could imitate the natural "equipment" of flying animals: "A bird is an instrument which operates according to mathematical laws, which instrument it is in the power of man to imitate" (CA, f. 434 r/161 r–a). Leonardo's studies for flying machines seem to have been based more than any other of his studies on his conviction of the substantial mechanical uniformity of Nature. He believed that the mechanical formulas and principles used by Nature in its creatures, such as birds, could be imitated and reproduced by man. During these years this same faith led Leonardo to immerse himself in the study of human anatomy and to frequently emphasize that the principles of mechanics constitute the indispensable introduction to a treatise on human anatomy.

Leonardo's studies of flying machines were a dream, but a dream nurtured by the hope of opening up vast horizons through a new approach. His dream was rooted in the intuition of the substantial unity of the entire realm of Nature, which used the same simple, necessary laws to produce man, the earth, and the animals.

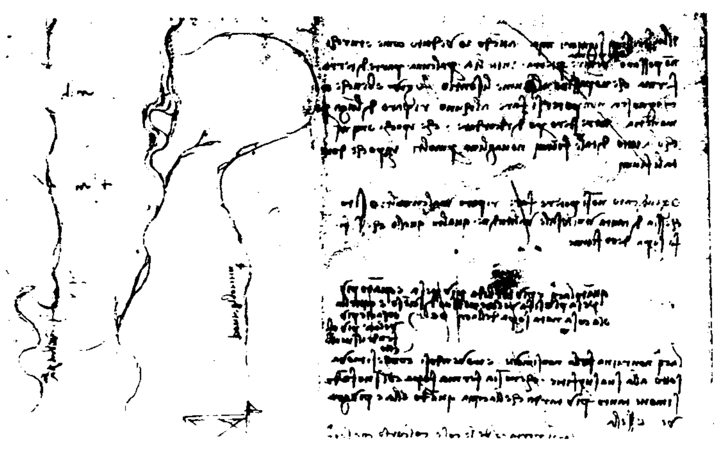
Leonardo's studies of flight broke off at the end of the 1400s without having reached a real conclusion; he took them up again around 1505, compiling that extraordinary manuscript known as the Codex on the Flight of Birds, now in the Royal Library at Turin. By this time, through a careful comparison between the muscular power of birds and that of man, Leonardo had realized that man did not have the strength necessary to lift a flying machine. From this point on, flying machines with beating wings disappeared from his studies, and he devoted himself passionately to another, much more realistic possibility: that of "sail flying" like a glider. This new attempt also failed to produce concrete results. Nevertheless, it led Leonardo to important investigations of the mechanics of the flight of birds, of the nature of air, and of the formation and role of winds and air currents. These studies occupied a significant part of Leonardo's activity from 1500 to 1514, and in them the comparison between water and air, swimming and flying, fish and birds becomes increasingly important: "Write of swimming underwater and you will have the flight of the birds through the air" (CA, f. 571 Ar/214 r-d). The universal rule of the four powers of nature found new applications in these studies of the mechanics of fluids, which, although rich in fundamental intuitions, remained at the stage of fragmentary notes and drawings. They awaited a comprehensive reformulation which Leonardo continually promised to do but which he never succeeded in carrying out.

Continual Wanderings (1499-1519)

Leonardo's first Milanese period came to a close with the tumultuous end of the Sforza domination of Milan in 1499 as a result of Louis XII's successful struggle to claim sovereignty over the region. At the beginning of 1500, in Venice, where he had moved with his friend and mathematics teacher Luca Pacioli following a brief stay in Mantua, Leonardo wrote a note on the cover of Paris MS. L that is worthy of the pen of Machiavelli in its conciseness and bluntness: "The duke lost his state, his property, and his freedom, and none of his works was completed for him".[79]

For Leonardo, who was almost fifty years old, there followed a period of continual exhausting travel in search of new patrons who could guarantee him the freedom to study and the comfortable life he had enjoyed while in the service of Lodovico Sforza. Among the few traces of Leonardo's brief stay in Venice are his studies of a series of fortifications on the Isonzo River (CA, f. 638 Dv/234 v-c: Fig. 84) intended to impede access from the mainland into the Venetian lagoon. In the Arundel MS. (f. 270 v) we find drawings and notes which refer to a "movable lock" which "I ordered in Friuli"; these certainly relate to Leonardo's stay in Venice.

When he left Venice, in the company of Pacioli, Leonardo headed South. In March 1501 he was in Florence, where he stayed until the summer of 1502. Leonardo's return to Florence after an absence of twenty years does not appear to have aroused any particular emotion in the city, which was now ruled by a republican government. Nor does he appear to have found great work opportunities there.



In a letter dated 3 April 1501, Pietro da Novellara, an agent of Isabella d'Este, described Leonardo as lacking in commissions and hence free to devote himself, in accord with his own inclinations, to those same scientific studies to which he had dedicated a large part of his later years in Milan: "he is hard at work on geometry, and cannot bear to touch a paintbrush". In a second letter of the same year, dated 14 April, Novellara provided more detailed information, recounting a visit to the master; "in short, his mathematical experiments have distracted him so much from painting that he cannot suffer the brush".[80]

This lack of commissions probably led Leonardo to abandon his pleasant *otia* and to accept, in the summer of 1502, the invitation of Cesare Borgia, the notorious Duke Valentino, to follow him as Architect and General Engineer in the military campaign intended to give him, with the support of his father Pope Alexander VI, a vast dominion in central Italy. Leonardo travelled with Cesare through the Marches, Umbria, and Romagna, inspecting strongholds and proposing systems of defence, with ample authority and substantial responsibilities.[81] He participated in the capture of the town of Urbino, where he was undoubtedly attracted by the treasures collected by the Montefeltro family in their famous library, which Cesare sent to Rome. Leonardo probably searched there for the scientific texts he had begun to collect so ardently during his years in Milan. "There is a complete Archimedes in the possession of the brother of Monsignor of Santa Giusta in Rome. The latter said that he had given it to his brother, who lives in Sardinia. It was formerly in the library of the Duke of Urbino, and was carried off from there in the time of the Duke Valentino", Leonardo wrote in a memorandum of 1515 (CA, f. 968 Br/349 v-f). Wherever he went, Leonardo observed and took measurements; in Paris MS. L he recorded the most diverse observations. His most important achievement from this phase is the famous map of Imola preserved at Windsor (RL 12284: Fig. 85). This map reveals the skill developed by Leonardo in map making, a fundamental tool of urban planning and military architecture (this particular map was made for the latter purpose). Here Leonardo adopted and perfected the geometrical relief methods which Alberti had used in the *Descriptio Urbis Romae*. The town of Imola is inscribed in a circle radiating from a centre. From this point the town spreads out in a perfectly detailed drawing, maintaining, thanks to accurate measurements, the exact proportions of streets, squares, and buildings. Leonardo also used different colours to distinguish streets from squares, waterways, and houses.[82]

After his experience with Cesare Borgia, Leonardo returned to Florence in the late spring of 1503, at the height of the war between the Florentine Republic and the city of Pisa. This circumstance led to his first technical commission from the city government. He was asked to give his opinion on how to deviate the course of the Arno in order to flood the city of Pisa and force it to surrender. It is not clear what part Leonardo played in this project of an unmistakably Brunelleschian flavour, a project which also involved other engineers. The digging of the deviation canals was begun in the summer of 1504 with the use of powerful equipment and the participation of about two thousand workers. But the results were extremely disappointing and work was soon abandoned. We can relate to this project several maps and reliefs of the Pisan territory in Madrid Codex II (Fig. 86 and Pl. XI), in which Leonardo gave special attention to the river network. Following a method he had initiated during his years in Milan and developed while in the service of Cesare Borgia, Leonardo inserted his projects into a scrupulous cartographic, hydrographic, and orographic documentation of the region in question.[83]

It is possible that the two drawings of excavating machines (CA, ff. 3 r/1 v-a: Fig. 87; and 4 r/1 v-b: Fig. 88) are also related to Leonardo's participation in this project. As Carlo Pedretti has

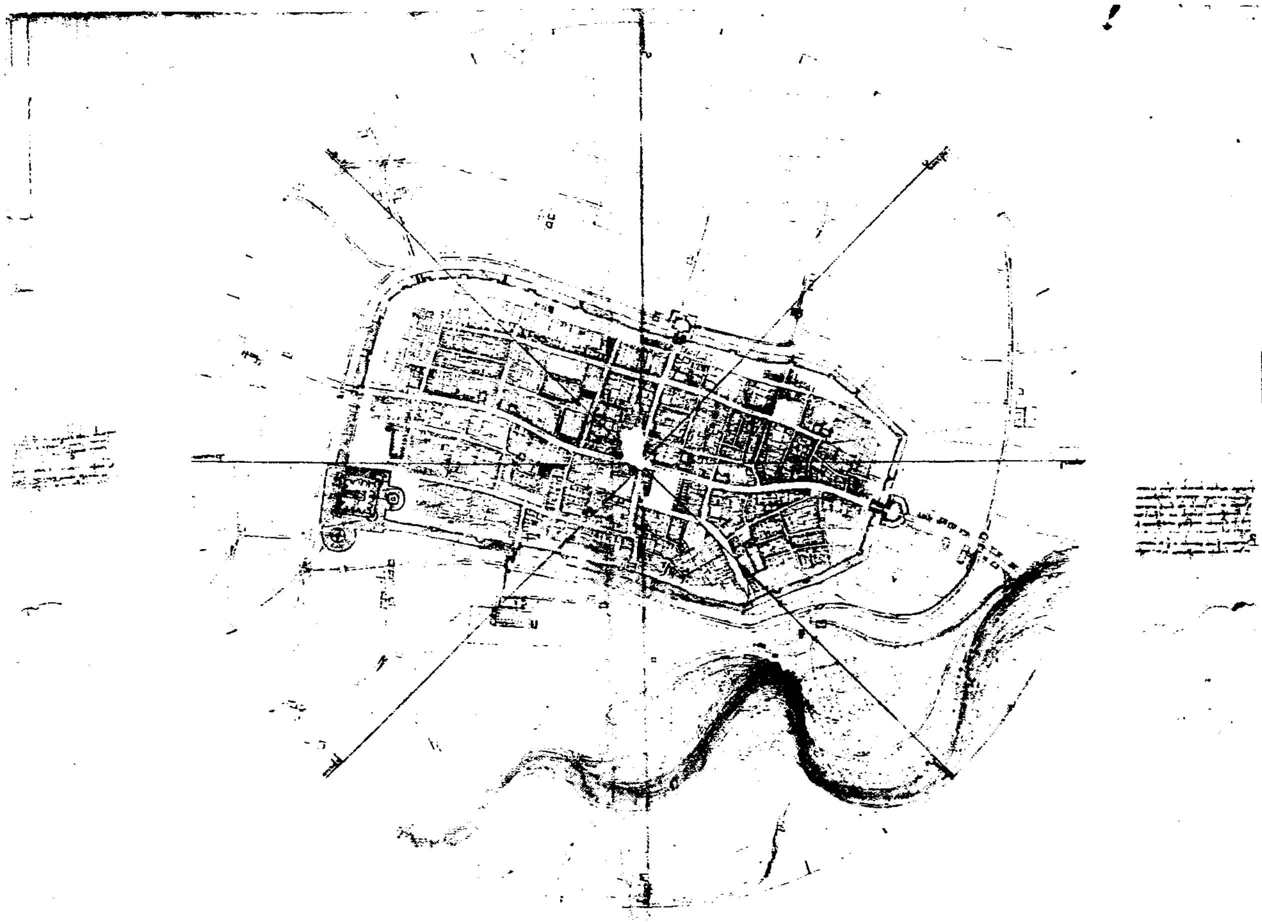
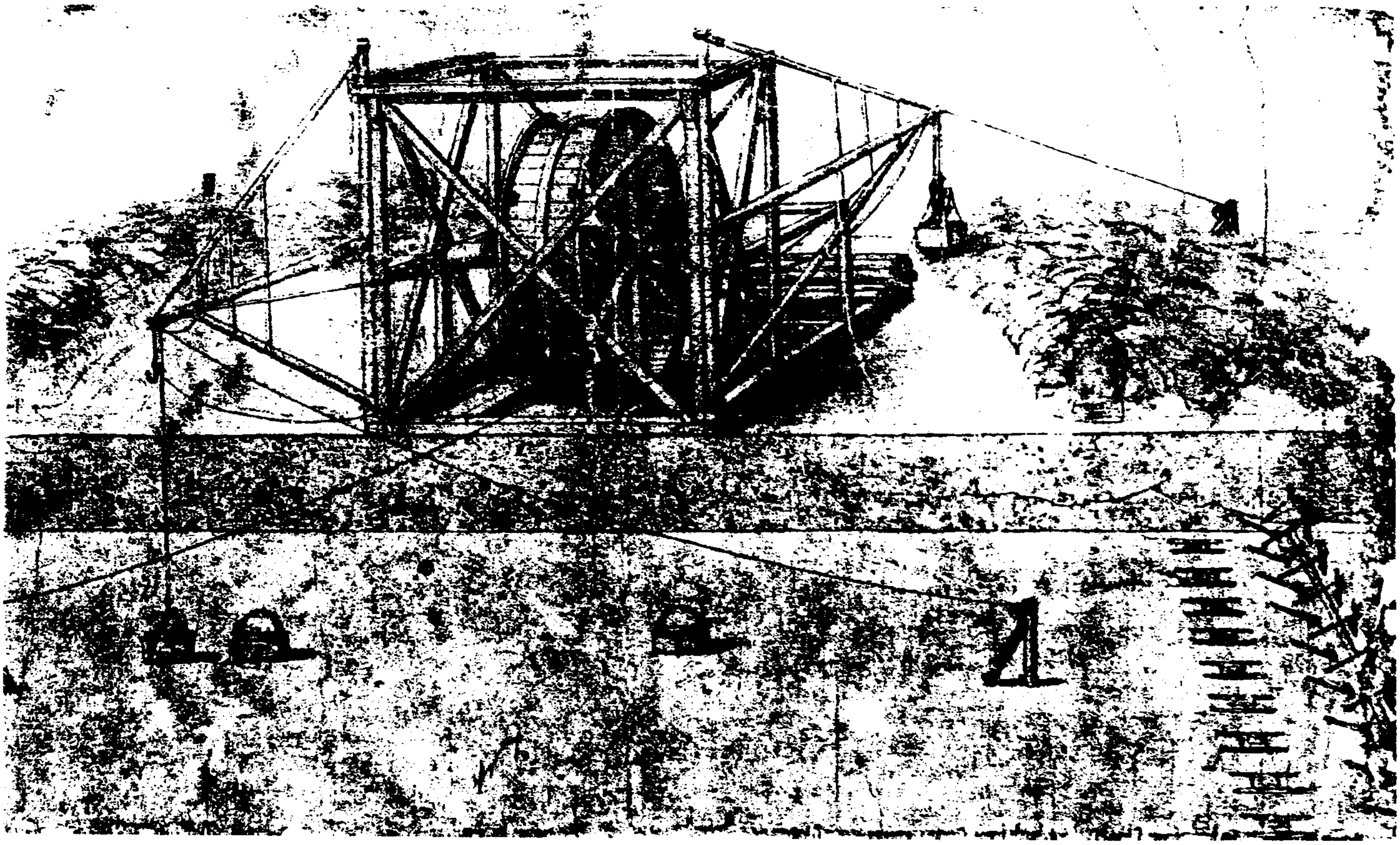


Fig. 85. RL 12284. The plan of Imola.



37. CA, f. 3 r/1 v-a.

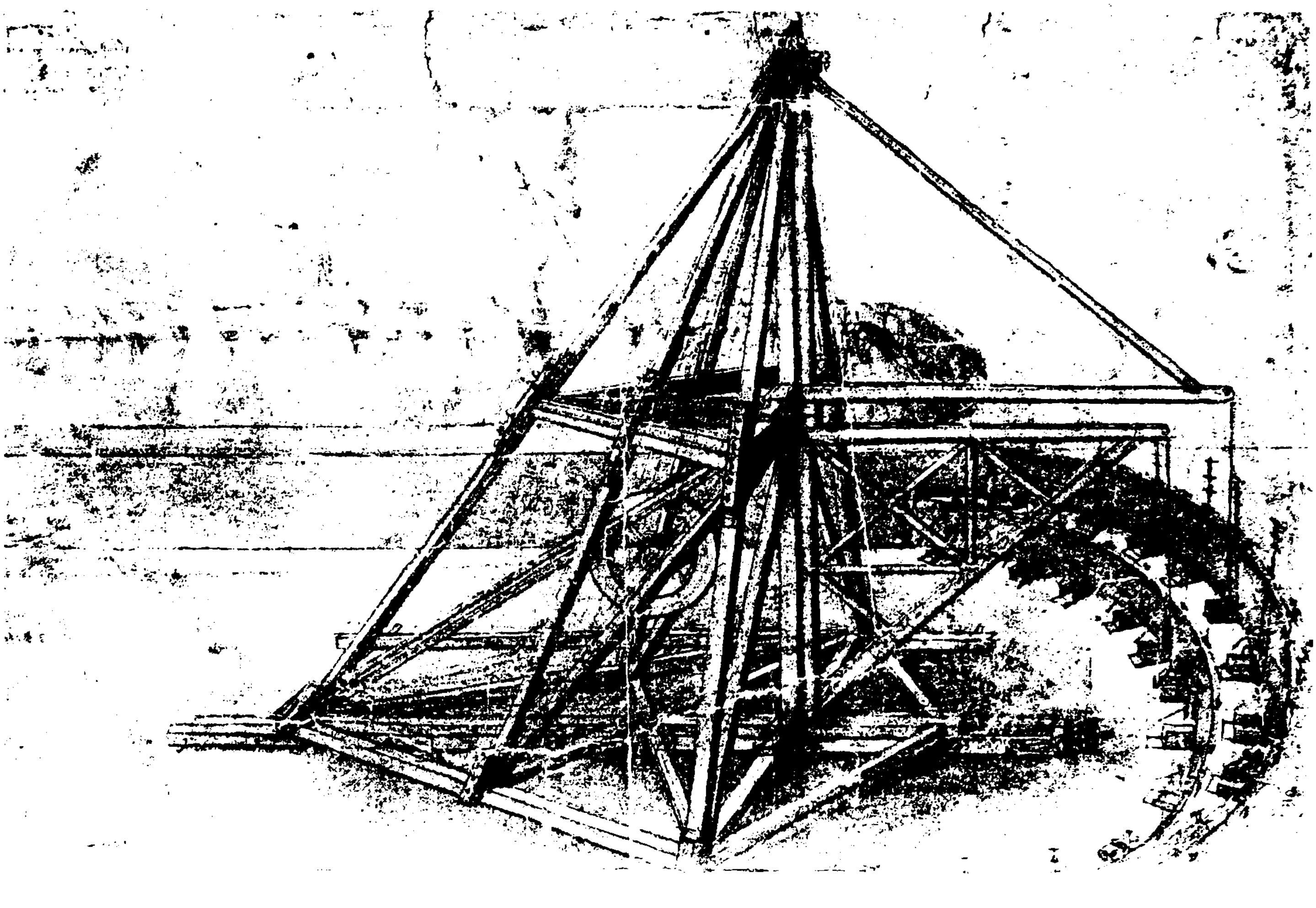


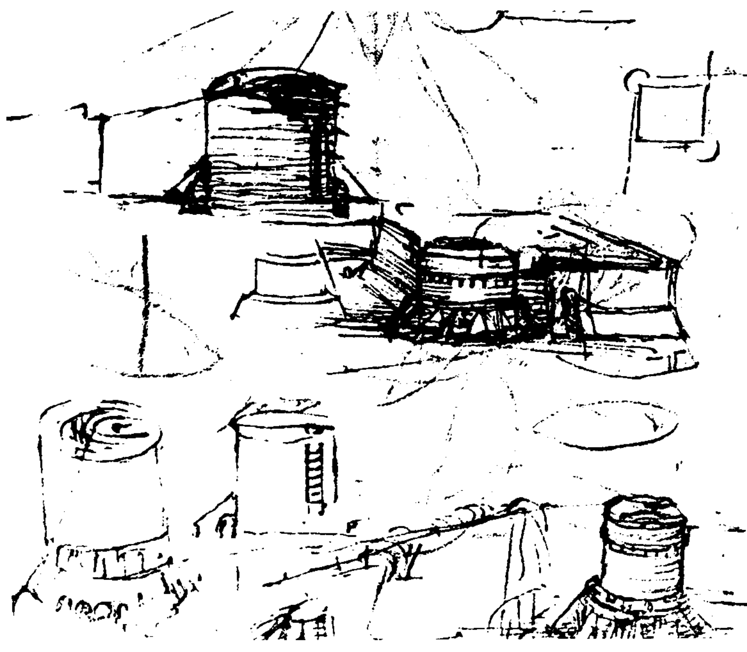
Fig. 89. RL 12279. Project for a canal to make the Arno navigable from Florence to Pisa.

established, the two sheets were originally joined and show the different operation of each of the two gigantic excavating machines working on the same canal.[84] In this way Leonardo intended to clearly demonstrate the superiority of the machine proposed by him (f. 4 r) as opposed to the traditional one (f. 3 r). This superiority consisted in the fact that his machine operated inside the canal and could move forward on rails thanks to a screw device. In addition, it had an effective counterweight to the heavy buckets of earth, in the form of other buckets in which the workers were lowered into the canal and lifted back up to ground level.

The design for the excavating machine with the counterweight system (see also the earlier drawing of an excavating machine in Madrid MS. I, f. 96 r) might, on the other hand, be related to a different series of studies, also from 1503, dealing with a project for the canalization of the Arno River in order to circumvent the unnavigable section between Florence and Empoli. There are a considerable number of studies in Madrid MS. II and in several magnificent drawings at Windsor (Fig. 89) where we see once again Leonardo's characteristic close attention to cartographic, orographic, and hydrographic detail. This project envisaged the construction of a canal that would extend from Florence along the plain between Prato and Pistoia, circumventing the tortuous bends in the Arno between Montelupo and Empoli, and rejoining the course of the river near Vico Pisano. The new canal, which had a semicircular shape, implicated large-scale works such as the construction of a tunnel through the hill at Serravalle, outside Pistoia (see Madrid MS. I, f. 111 r: Fig. 90). In order to keep a steady flow of water in the canal, Leonardo envisaged the construction of a large reservoir in the Val di Chiana.[85] At a certain point he must have submitted this project to the government of the Florentine Republic, as suggested by several notes in which he insisted, undoubtedly to justify the size and cost of the undertaking, upon the economic benefits that would be derived from it: "this canal will benefit the country, and Prato, Pistoia, and Pisa as well as Florence will gain two hundred thousand ducats a year, and will lend a hand and money to this useful work..." (CA, f. 127 r/46 r-b). Despite Leonardo's optimistic predictions, the Florentine government did not let itself be tempted to undertake a project which it must have considered impossible to carry out.

The important artistic commission that Leonardo received in 1503 from the Florentine Republic (to paint a fresco commemorating the victory of the Florentine army over the Milanese troops at Anghiari in 1440) absorbed much of his energies, but did not cause him to neglect his beloved studies of geometry, which he was probably still conducting under the guidance of Pacioli. Leonardo was particularly involved in the compilation of a treatise on the transformation of geometrical figures. A new commission, this time from Jacopo IV Appiani, lord of Piombino, took Leonardo away from Florence in 1504. In all likelihood with the encouragement of the Florentine Republic, which was allied to Appiani, Leonardo acted as his consultant in matters of military fortifications (Fig. 91).[86] When he returned to Florence, he once again immersed himself in the study of geometry and in the preparation of the *Battle of Anghiari*. In 1505 he again took up the study of anatomy with some intensity. As we have already mentioned, 1505 was also the year Leonardo compiled the Codex on the Flight of Birds. In May of 1506 he was again forced to interrupt his studies when he was imperiously recalled to Milan by the French governor, Charles d'Amboise, apparently for works of painting and architecture. Between 1506 and 1507 he continually travelled back and forth between Milan and Florence, where he had to return because of his litigation with his brothers over their uncle's estate; he was also being pressured by the Florentine government to finish the *Battle of Anghiari*. Needless to say, it was difficult for Leonardo to complete anything under such conditions.

Leonardo spent the last part of 1507 and a good part of 1508 in Florence. He continued to study anatomy (this was his most intense, fruitful period in this field), taking advantage of the access he had gained to the city hospital. And while he was dissassembling the constituent organs of the human machine in order to understand its mechanical secrets, Leonardo also turned his attention to the



machine of the earth, which he explored with equal anatomical carefulness in his search for solid proof of the close symmetry between man (the "lesser world") and the cosmos.[87] By this time geometry and mechanics, anatomy and geology, in a continual exchange of concepts, principles, and analogies, were Leonardo's preferred field of activity, as can be seen in his manuscripts from these years: the Codex Hammer, the anatomical sheets at Windsor, and the Arundel MS., which was begun in Florence at the home of Piero di Baccio Martelli in 1508.

During this period of restlessness Leonardo's interest in practical technical applications seems to have dwindled to the point of disappearing altogether. His propensity for studies of a theoretical nature grew with his conviction that all knowledge presupposes the mastery of geometry. The few surviving applied studies from this time were increasingly based upon the natural laws which Leonardo was in the process of formulating. He displayed the same tendency in Milan, where he moved at the end of 1508. There he further developed the anatomical and geological studies he had begun in Florence, always insisting upon the close connection between cosmos and microcosm. He intended to compile treatises on these subjects. He maintained his interest in geometry, especially in the geometrical transformation that he believed to be a formidable tool for the art of painting and the investigation of solid bodies. He used such transformations in his studies of myology (the lengthening and shortening of muscles) and hydrodynamics (the flow of blood in the arteries and valves of the heart, but also the flow of water in winding rivers).[88]

Leonardo's attempt to derive practical applications from theoretical premises is evident, for example, in the treatise he was planning to write on water, the key element in his dynamic universe. The table of contents of this treatise shows that the first chapters were to deal with theoretical questions, from which the sections of hydraulic engineering would be derived (Codex Hammer, f. 15 v: "Book 10: Of River Repairs. Book 11: Of Conduits. Book 12: Of Canals. Book 13: Of Machines Turned by Water. Book 14: Of Raising Water..."). Only occasionally do technological projects of the type seen so frequently before 1500 appear in Leonardo's studies from these years. His progressive involvement in theoretical questions seems to have brought with it a lessening of his interest in practical applications. We find confirmation of this even in the kind of celebratory scholarship which we have so often warned against here, which presented Leonardo as the sensational inventor of every modern device: it is widely recognized that all of his supposed discoveries took place before the end of the fifteenth century.

By this time Leonardo worked on specific technical projects only when asked to do so by his patrons. This is the case of the project he worked on between 1508 and 1510, probably by order of Louis XII, to bypass the narrow portion of the Adda River near the Tre Corni at Paderno, of which there remain elements of the complicated and perhaps unrealizable (at any rate, unrealized) solutions devised by Leonardo (Fig. 92).[89] Taking advantage of the generous patronage of the king of France, who allowed him a great deal of free time, Leonardo was able to develop his "vocation", which seems no longer to have been that of an engineer, but rather that of a scientist.

This tendency to abandon the activity of engineer remained evident during the years Leonardo had still to live after he was forced to leave Milan in 1513 as the result of the French defeat and the return of the dukedom of Massimiliano Sforza. Leonardo, now an old man, was once again forced to set out on tiring travels in search of new patrons. He stopped in Florence, where his old patrons the Medici had returned to power. Then he went on to Rome, in the service of one of the members of that family, Giuliano de' Medici, the brother of Pope Leo X. In exchange for a salary and protection, Leonardo placed his skills as a hydraulic engineer at Giuliano's disposal, advising him on the project for draining the Pontine marshes (see Pl. XV). This was later carried out but it is unlikely that Leonardo played a significant role in it. In Rome Leonardo occupied himself with making parabolic mirrors (Arundel MS., f. 279 v) by connecting many pieces of glass. He also studied devices for manufacturing

Fig. 92. RL 12399.

rope, which are found among his last technological drawings in the Codex Atlanticus (ff. 12 r/2 v-a: Fig. 93; and 13 r/2 v-b: Fig. 94): one of these bears the Medici symbol of the diamond ring, which proves that he received the commission from Giuliano. This sporadic return to practical technical activities can be explained by the pressure of immediate, specific demands. But as soon as possible he resumed the study of geometry, optics, and anatomy; the latter led him to frequent the Roman hospital of Santo Spirito, which at a certain point he was forbidden to visit on account of an accusation of necromancy.

In the summer of 1516 the lily of France once again brought good fortune to Leonardo. The new king, François I, invited Leonardo to follow him to France, offering him exceptional rewards and honours. Leonardo's main activity during these years was the project for a new royal palace at Romorantin, which was linked to a whole series of projects for the canalization of the waterways of the region.[90] None of these projects was ever carried out. In reality, Leonardo did not work a great deal in France. His mere presence in a court that would attract talents of every kind, particularly from Tuscany (Cellini, Guido Guidi, and so on), justified the excellent treatment he received and the payment of a pension to him as "*premier peinctre et ingénieur et architecte du Roy*". The account of Antonio de Beatis, who came to France with Cardinal Luigi of Aragon and visited Leonardo on October 10,

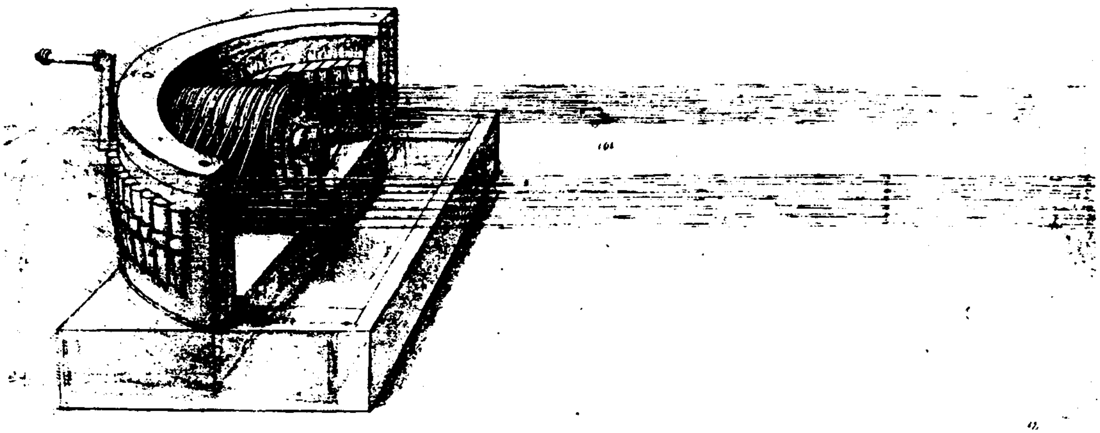


Fig. 93. CA, f. 12 r/2 v-a.

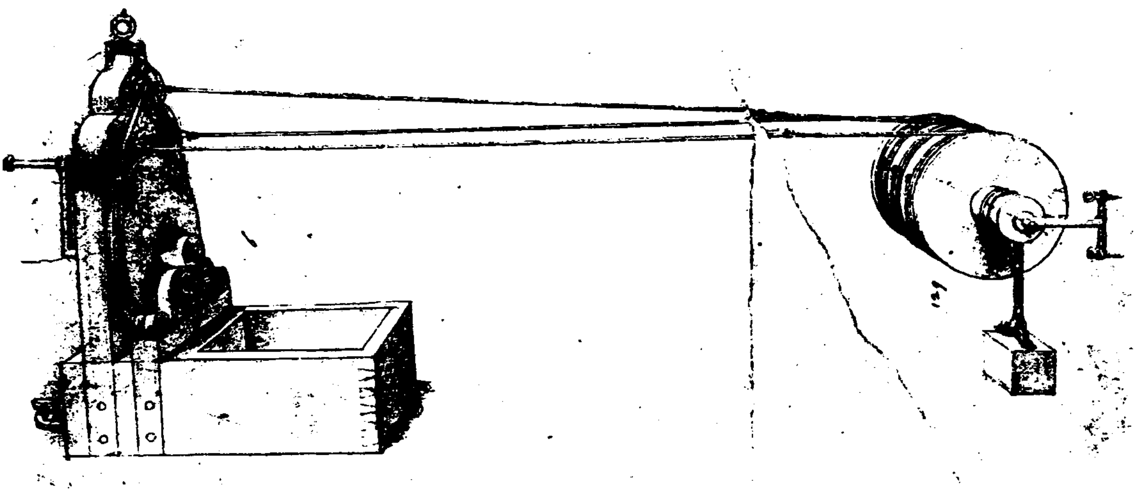


Fig. 94. CA, f. 13 r/2 v-b.

1517, describes a man who evoked admiration not so much for his present activities, which were impeded by his age, as for the extraordinary knowledge he had succeeded in acquiring in every field of learning.[91] The accounts of those who saw Leonardo during the last years of his life paint a picture of a wise, learned old man, quite removed from that of a modest technologist. In a passage describing the extraordinary affection of François I for Leonardo, Benvenuto Cellini, correctly interpreting the metamorphosis that had taken place, calls the aged Leonardo "a very great philosopher":

> King François, who was extremely taken with his great virtues, took so much pleasure in hearing him speak, that he was separated from him only for a few days out of the year... I do not wish to neglect to repeat the words I heard the king say of him, which he said to me... that he believed that there had never been another man born in the world who knew as much as Leonardo, not so much about sculpture, painting, and architecture, as that he was a very great philosopher.[92]

Leonardo and the Engineers of the Renaissance

In recent years several scholars have suggested that the traditional view of Leonardo as an engineer and inventor should be revised. Solidly basing their work on a series of important studies of formerly neglected manuscripts of the many engineers who were active before and during Leonardo's time, these scholars have shown that many of his presumed sensational discoveries can be found in earlier works (especially in Taccola and Francesco di Giorgio and, at times, even in mediaeval manuscripts of the French and German tradition, which echoed the great classical tradition). This holds true for the diving suit, the automobile, the parachute, the crankshaft, the tank, and the multiple-barreled cannon. Beck[93] and Feldhaus,[94] the first great historians of Renaissance technology, had already indicated that this was the case, but other scholars did not follow them. More recently the work of Reti,[95] Gille,[96] Prager,[97] Scaglia,[98] and others has provided evidence that is too probing to be ignored.

At the same time, proof has been found in Leonardo's manuscripts that he carefully attempted to master the technical solutions introduced by the engineers of antiquity and by the most respected engineers of his own time. Suffice it to mention his fruitful contact with Francesco di Giorgio and the evidence in his notes of the attention he dedicated to the studies of that great Sienese engineer. In fact, Leonardo copied many passages from a treatise by Francesco di Giorgio into Madrid MS. II.[99] At a certain point he also had at his disposal a magnificently illustrated copy of Francesco di Giorgio's treatise on architecture, with its wealth of carefully executed drawings of machines and mechanical devices; there are several autograph notations by Leonardo in this manuscript (Fig. 95).[100]

This more serious historical approach, which assesses Leonardo's career within the framework of the context in which it developed, considerably modifies our vision of him. He appears, in fact, to have had a background, interests, working method, and type of career similar to the other Renaissance engineers with whom traditional historiography had disdainfully contrasted him. Thus, present-day scholars, instead of dwelling on the great loss represented by the dispersal of Leonardo's manuscripts, use his papers as a source for the reconstruction of fundamental aspects of the technical knowledge of the fifteenth and sixteenth centuries, for many of which they provide the only surviving documentation.

This is the result of a complete reversal of historical orientation, of which the most significant example is the book on Leonardo and the engineers of the Renaissance by the outstanding philologist and historian of technology, the late Bertrand Gille.[101] Overturning the traditional celebratory image of Leonardo as a solitary, misunderstood innovator in every field of technology, Gille emphasized the many similarities between Leonardo and other engineers of his time, based upon a remarkable amount of documentary evidence. But Gille's strongly polemic stance toward the traditional adulatory view of Leonardo led him to excesses in the opposite direction. In Gille's work, in fact, the characteristic aspects of Leonardo's technology disappear into the melting pot of technical solutions, working methods, and professional activities typical of all the Renaissance engineers.

This is an equally unacceptable conclusion, which neither helps us to understand Leonardo nor to

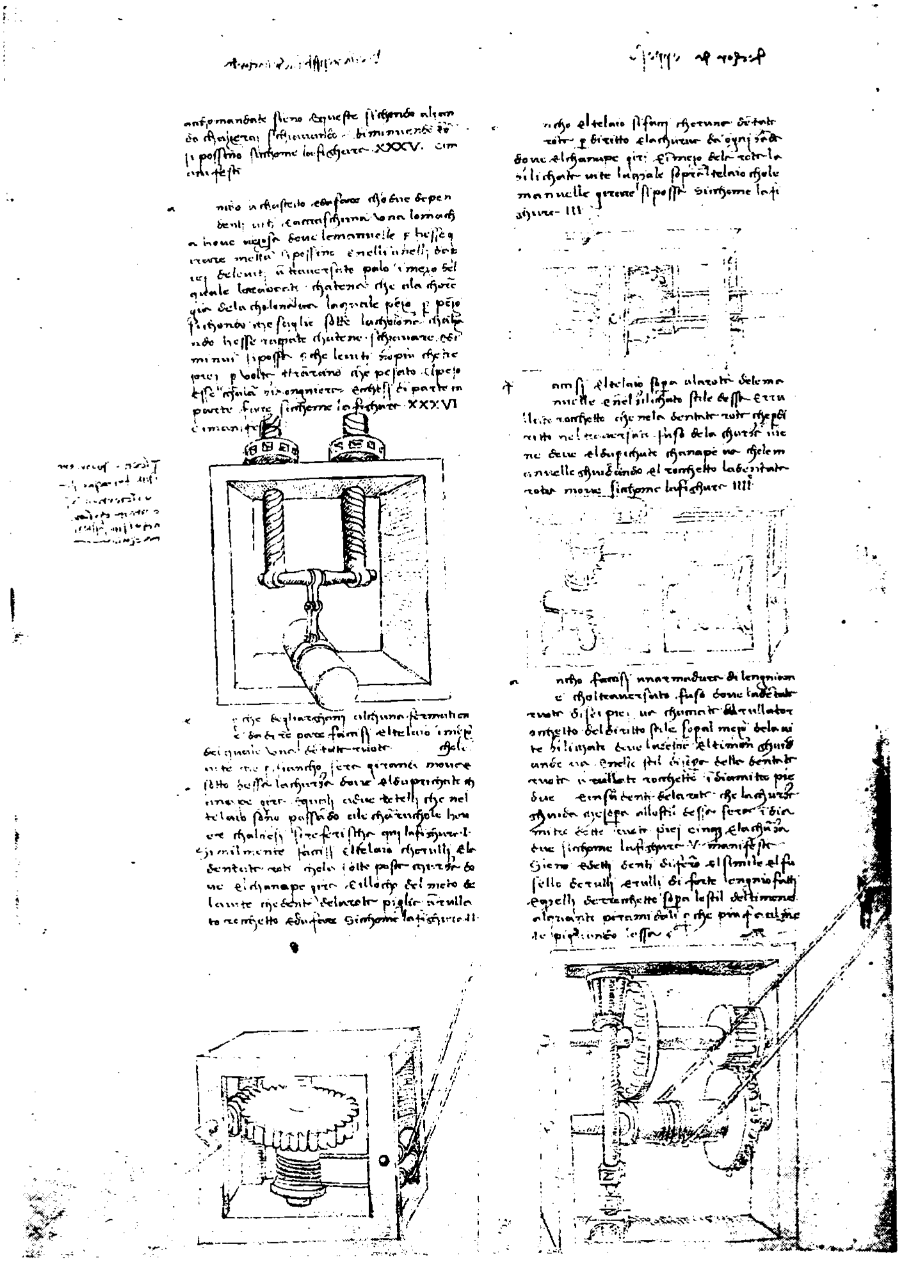


Fig. 95. Francesco di Giorgio, Ashburnham MS. 361, f. 44 v. Leonardo's autograph writings are at the top of the two columns of writing.

grasp the nature of his relationship to other engineers of his time. Gille's work, in addition to suffering from a view of the evolution of technology as a linear process without abrupt developments, also reflects the limitations of a study of Leonardo's texts which lacks a criterion for chronological ordering. Gille was unaware of the distorting effects of his separation of Leonardo's studies of applied technology (machines and mechanical devices) from his more theoretical scientific studies, which he unjustly neglected. Following Gille, other scholars have stressed the substantial similarities between Leonardo's work and that of other great engineers of the Renaissance.[102]

The brief outline of the chronological development of Leonardo's career as an engineer given in the preceding pages offers the possibility of posing the problem in more balanced terms. Leonardo's early career is characterized by attitudes, practices and interests, that were common among other engineers of his time. The evidence that he was trained in Verrocchio's workshop is incontrovertible;

and it is safe to assume that at the very beginning of his career as an engineer Leonardo chose Brunelleschi as his model. But in the course of a half century Leonardo's career underwent a significant evolution, which must be taken into account. The turning point occurred a few years after Leonardo moved to Milan. His manuscripts began to record with increasing frequency the evidence of his effort to base his technological studies on entirely new foundations. He desperately sought books and experts who could help him with Latin or Greek texts; he struggled to learn Latin, asked himself new questions, investigated the causes of mechanical effects of which he had a practical mastery. With the passing years this tendency became increasingly marked and involved every aspect of Leonardo's activity, not only engineering. Indeed, it was as a painter that Leonardo first raised fundamental questions. In the mid-1480s Leonardo's entire professional personality began to undergo a process of transformation. He systematically practised the observation and imitation of Nature in every field: man, animals, the earth, the great physical agents of water and air. The science of mechanics seemed to offer him, with its law of the four powers, the key to understanding every natural phenomenon. Following classical and mediaeval tradition (Archimedes and the science *de ponderibus*, in particular), often with the assistance of others, Leonardo realized that mechanics was useless without geometry (it was not by chance that he defined mechanics as the "paradise of the mathematical disciplines"). In the geometrical studies, in which he passionately immersed himself at the end of the fifteenth century, we can recognize Leonardo's habitual method: he drew upon the knowledge of friends (in this case, Pacioli), took as much as he could from diligently acquired books and manuscripts (Euclid, Archimedes, etc.), and then undertook original research and reflection.

No other Renaissance engineer reveals a similar evolution. Nor did any of them achieve results like those that Leonardo obtained. This is not to say that he formulated a coherent system of knowledge, i.e. a well-founded, comprehensive scientific encyclopaedia. As we have said, he achieved both spectacular and modest results in every field of activity: he never mastered Latin perfectly; in the field of mechanics, apart from some brilliant ideas, he never succeeded in bringing into focus the fundamental concepts of force, percussion, and movement; his prolonged efforts to learn geometry did not produce great results, nor did his splendid drawings and acute insights change the face of the science of anatomy, or geography, or physics, or optics (where he achieved what were perhaps his most advanced results). He was planning to write general works in each of these fields, recording many solemn beginnings or ambitious tables of contents which he never followed up. He did not escape the limitations of his early training, maintaining to the end the characteristic "workshop" style of jotting down brief notes, each unrelated to the other. This typical procedure by "cases", is also found in Leonardo's more thematically organized manuscripts such as the Codex Hammer or Madrid MS. I.

Hence it is necessary to recognize that the limitations of Leonardo's training (which for that matter he never regretted, proudly declaring himself to be an "unlettered man" and a "disciple of experience"), and the scope of his ambitions, determined the substantial failure of his project of re-founding all of the arts and sciences on unified principles and procedures. But Leonardo felt the need to devote tremendous energy to this undertaking. And it is precisely this that distinguishes him from the other engineers of his time. It is likely that some of Leonardo's colleagues were more capable than he was as military architects, as builders of mechanical devices and machines, as hydraulic engineers. And it is certain that most of them kept the commitments they had made with greater regularity. But it does not appear that any of them ever felt the need to provide a more solid foundation for their activity, which remained based exclusively on procedures and practices acquired in the exercise of their art.

In fact, by the end of the fifteenth century there were considerable differences between Leonardo and other engineers of his time or of earlier generations. It was not by chance that this inconclusive, unreliable, moody man was the most sought after and honoured by patrons who were accustomed to treating their engineers in a very different way, by paying them for specific tasks. Perhaps the only Renaissance personality who can be compared to the mature Leonardo is Leon Battista Alberti. And it is not surprising that Alberti was not a practical technician but a highly learned humanist who had compiled influential artistic treatises and had used his vast knowledge of the classics to show the profession of the architect-artist in all of its complexity. He illustrated perfectly, in fact, how this profession implied — over and above a mastery of "*disegno*" — geometrical knowledge, complex technical know-how, and a precise notion of statics, not to mention notable capacities for the creation of "form" imbued with precise symbolic connotations. Such implications were the consequence of Alberti's awareness of the unity of principles and forces, which led him to insist upon the constant symmetries linking man, buildings, and the universe. A considerable amount of evidence shows that these Albertian themes attracted Leonardo, who at a certain point probably recognized in Alberti a model to follow.[103]

It is not, however, only the evolution and importance of Leonardo's investigations of general causes and laws, or the consequences that these produced on his way of dealing with practical applications, that distinguish him from other engineers of his time. As is made evident by a simple comparison of Leonardo's manuscripts with those of his colleagues, his technological drawings have a totally unique character and power. In this field as well, Leonardo's studies clearly reveal an evolution, from his early, somewhat uncertain, technological drawings to the progressive definition of a precise strategy of technological rendering which reached its height between the end of the 1480s and the beginning of the 1490s. Leonardo's incomparable ability as a technical draughtsman was not merely the fruit of his superior artistic ability. It derived from a deliberate "intellectual" attempt to consistently replace the working model, which he had previously used extensively, with the technical project in the form of a drawing. To obtain this result, in architecture as in sculpture, in the design of dynamically operating machines as well as in the depiction of human organs and their functions, Leonardo was the first to perfect a series of remarkable techniques that were destined to change the style, method, and function of scientific illustration. One would search in vain for anything similar in the notebooks of other Renaissance engineers. Carlo Pedretti's introduction to the present catalogue masterfully demonstrates the importance of the revolution in illustration introduced by Leonardo and its many important implications; hence I need not insist upon it here.

Leonardo's Method: From the Anatomy of Machines to the Man-Machine

The originality of the results that Leonardo's new approach enabled him to achieve is particularly evident in an important group of studies dating from the last decade of the fifteenth century, which I propose to analyze for their extraordinary character. These are highly effective studies of mechanics, of which it is impossible to find even vague precedents in the notebooks of Leonardo's contemporaries or in those of engineers of earlier generations. In addition, these studies are an eloquent indication of how the formulation of universal mechanical principles and the systematic use of geometry led Leonardo to project technological analysis beyond its traditional boundaries (i.e. machines and mechanical devices), and transform it into, among other things, a formidable tool for the study of the human body.

I wish to refer to the treatise on the mechanical elements (*elementi macchinali*) which Leonardo stated several times he had compiled, making numerous references to specific "propositions". The identification of this work has been discussed by, among others, Arturo Uccelli in his ponderous attempt to reconstruct Leonardo's books on mechanics in 1940.[104] Uccelli's work is a typical example, not advisable today, of the type of scholarship that was intent upon transforming into a comprehensive treatise a work that had been conceived in fragmentary form and had remained incomplete.[105] Uccelli conjectured that Leonardo's treatise on mechanics was divided into two parts, the first of which dealt with theoretical mechanics (motion, weight, force, and percussion), while the second collected and organized his notes on the "mechanical elements",[106] that is, according to Uccelli, on applied mechanics (mechanisms for pulling and lifting, pulleys, axles and wheels, screws).

The sensational discovery in 1966 of two Leonardo manuscripts in Madrid,[107] that offered fascinating new material related to his proposed treatise on mechanics, led historians to return to this question. In Madrid MS. I, which is devoted entirely to mechanics, we find a clear distinction between a section on theoretical mechanics and one on applied mechanics and specific mechanisms.[108]

Ladislao Reti, who played an important part in the discovery, was entrusted with producing the edition of the two manuscripts, which saw the light shortly after Reti passed away in 1974. He also wrote several essays on these manuscripts, particularly on the notes on mechanics in Madrid MS. I.[109] Reti was especially attracted by the initial section of the manuscript (which is the second in chronological order), in which he believed he could identify an advanced stage of the treatise on "mechanisms". Reti believed that this treatise corresponded to some extent to the "mechanical elements" to which Leonardo so often referred.

Reti's work, which strongly reflects his astonishment at the discovery of so much new Leonardo material, sometimes runs the risk of oversimplification. He believed that Leonardo's "mechanical elements" corresponded to an orderly series of reflections upon the "elements of machines", i.e. upon simple mechanisms, based on logical models which would, in actual fact, appear only three centuries later with the École Polytechnique in Paris, finding their definitive canonization with Franz Reuleaux in the mid-nineteenth century.[110]

Once again, the urge to emphasize Leonardo's sensational prophecies led to serious misunderstandings. In reality, Leonardo's many references to the treatise on "mechanical elements" leave no room for doubt as to the nature of the text, nor do they allow it to be related to a detailed analysis of mechanical devices. In a text in the Codex Atlanticus (f. 444 r/164 r-a), which Pedretti dates to about 1500,[111] Leonardo states that a body that descends along a 45° angle "becomes half its natural gravity, as I proved in the fifteenth conclusion of the fourth book of mechanical elements composed by me". In another passage in the Codex Atlanticus (f. 161 r/58 r-a, *c.* 1503-5)[112] we read: "Of two cubes which are double the one of the other, as is proven in the fourth [book] of mechanical elements composed by me"; and again in the Codex Atlanticus (f. 220 v/81 v-b, *c.* 1508):[113] "Mechanical elements. Of a weight proportional to the force that moves it, we must consider the resistance of the medium in which that weight is moved, and I shall write a treatise on this". We find other references in Paris MS. I (f. 22 v, 1499): "By the ninth [proposition] of the second [book] of elements, which says: The centre of every suspended weight comes to rest beneath the centre of its support..."; and finally, in the Codex on the Flight of Birds (f. 12 v, *c.* 1505): "If the bird wishes to descend head first, with such obliquity as would turn it upside down, this cannot happen because the lighter part would be below the heavier, and the light would come to descend before the heavy, which is impossible, as proven in the fourth [book] of mechanical elements". Other references to the "mechanical elements" are in the anatomical studies at Windsor,[114] especially the ones dating from 1508-10, where Leonardo mentions the "book on mechanical elements, with its practice" (RL 19009 r; K/P 143 r); on another sheet he again refers to the "fourth [book] of mechanical elements", where it is proven that "a longer lever has more power" (RL 19010 v; K/P 147 v).

The tenor of the passages quoted above unequivocally shows that Leonardo's references have nothing to do with a treatise on the "elements of machines", but rather with his "elements of mechanics". In fact, Leonardo refers to a division of the treatise into two parts, one theoretical and one practical. In addition, it is clear that the treatise included sections on the duplication of the cube and the theory of centres of gravity, of levers, and the inclined plane. In particular, the fourth book, which is the one Leonardo mentions most frequently, presented questions of general theoretical mechanics, while the only reference to practical applications is in the passage from the Codex Atlanticus which suggests taking into account the interfering influence of the medium when calculating force and resistance.

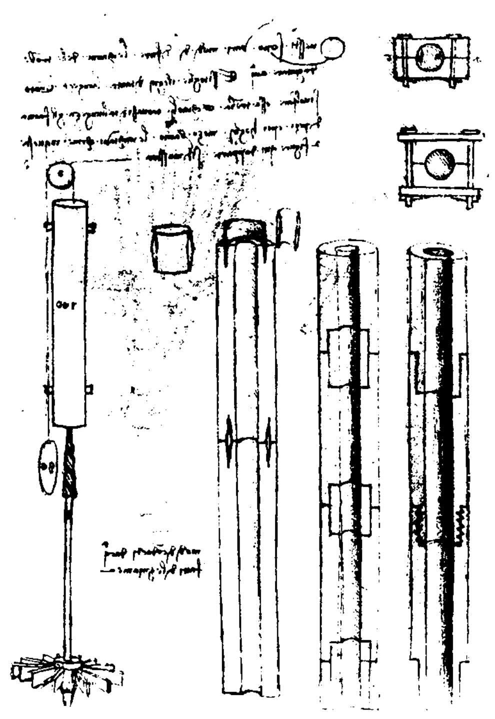
In all likelihood, "mechanical elements" is the title under which Leonardo intended to collect his reflections on mechanics. Following the model of classical and mediaeval statics, the role of geometrical analysis was crucial for Leonardo. He must have intended including in this treatise sections on the theory of the four "powers" of Nature (motion, weight, force, and percussion), and reflections upon centres of gravity and on methods for determining them, as well as the traditional analysis of simple machines. The practical portion would have included single and combined uses of mechanical devices and systems for optimizing them, along with the machines for producing them.[115] This also corresponds to the overall ordering indicated in many of Leonardo's memoranda.

Thus Leonardo's "mechanical elements" do not indicate a treatise on mechanisms, but rather on all mechanics. The very expression "mechanical elements" precisely reflects this function, in keeping with traditional terminology. "Mechanical elements" is an expression much like Euclid's "geometrical elements", where the word "elements" is equivalent to "foundations" or "principles". Another even more direct model was provided by a text which strongly influenced Leonardo, the *Elementa Jordani super demonstrationem ponderis* — a text on theoretical mechanics (i.e. mechanical principles) like the one Leonardo intended to compile.

Having clarified the true nature of Leonardo's treatise on "mechanical elements", we must recognize that the emphasis placed by Reti on the extraordinary penetration with which Leonardo analyzed the principles and criteria of the functioning of machines in Madrid MS. I is totally justified. The most remarkable portion of the manuscript is certainly the first part, where Leonardo analyzed in detail a series of mechanical devices, lingering over their most efficient characteristics and evaluating their power and resistance, construction materials, and methods of application (Figs 96-98).[116] He also gave great attention to the friction produced during operation, attempting to devise solutions for lessening it (Fig. 99). What we have here is a veritable "anatomy" of machines, often presented with powerful drawings that reveal an exceptional graphic mastery. The idea of a "dissection" of machines was, in fact, very clear in Leonardo's mind:

> All such instruments will generally be presented without their armatures or other structures that might hinder the view of those who will study them. These same armatures shall then be described with the aid of lines, after which we shall describe the levers by themselves, then the strength of the supports... (Madrid MS. I, f. 82 r).

Technological drawing plays a leading role here. It allows Leonardo to skilfully analyze these devices and to reassemble them with an illuminating range of different techniques of illustration based upon an exceptional mastery of perspective. The devices are seen from various points of view, in plan, in exploded views, in geometrical diagrams. Often the relationship between a device and a machine is captured with synthetic effectiveness by a drawing, as in the screw-jack with anti-friction bearings on Madrid MS. I (f. 26 r: Fig. 100), or in the note referring to the device for transforming circular motion into alternating motion (Madrid MS. 1, f. 12 v: Fig. 101) as particularly appropriate for a mechanical saw, like that drawn on folio 1078 Ar/389 r-a of the Codex Atlanticus (Fig. 102). Leonardo attempted to break down into a numerically finite catalogue the components or "organs" which make up the infinite variety of machines or "organisms": "Once the instrument has been created, its operational



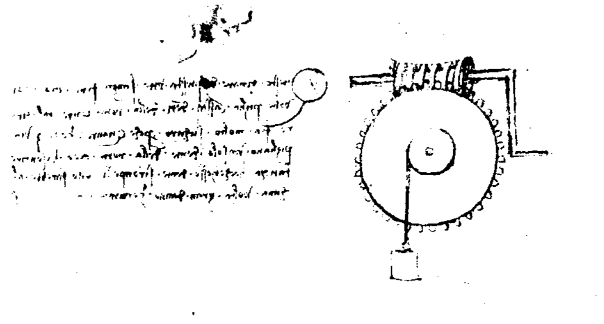


Fig. 98. Madrid MS. I, f. 17 v (detail). Toothed wheel and worm screw.

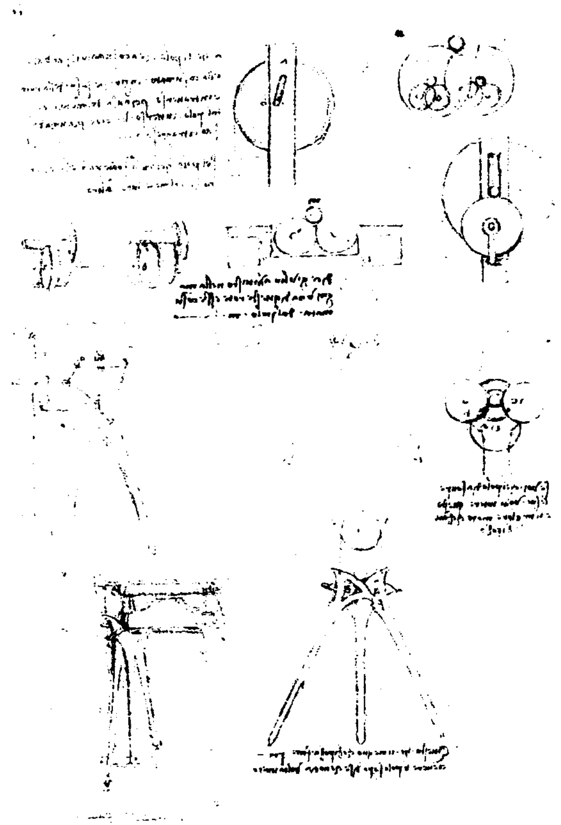


Fig. 99. Madrid MS. I, f. 12 v. Studies of devices to reduce friction.

Fig. 100. Madrid MS. I, f. 26 r (detail).

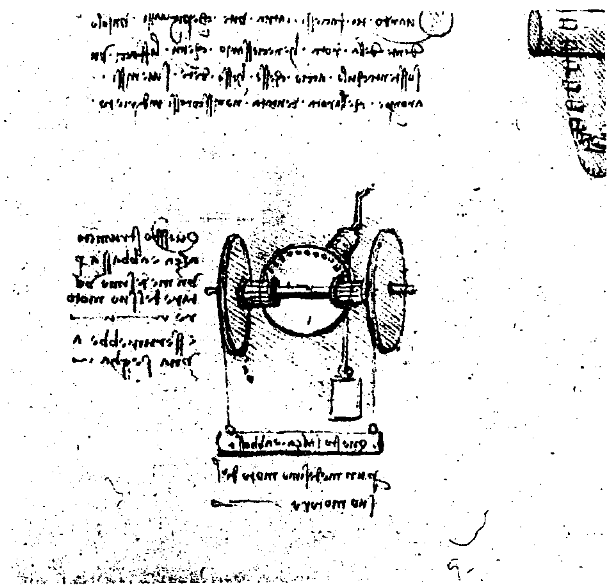
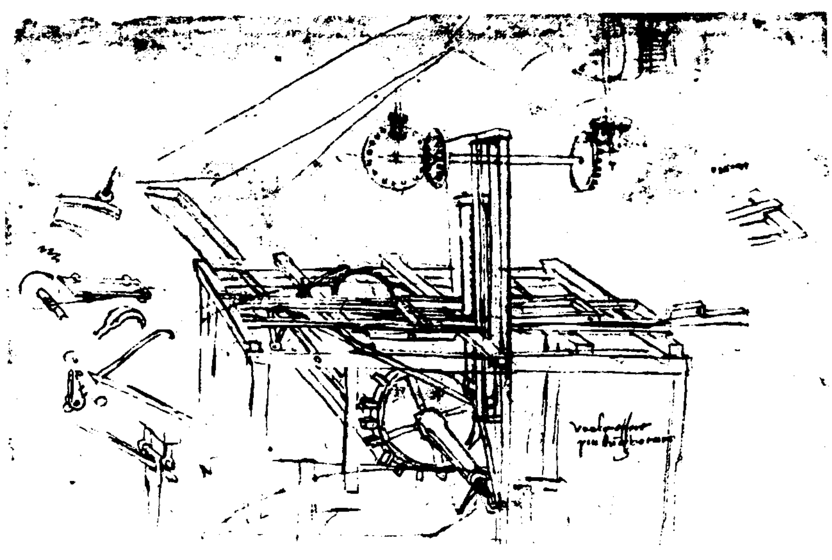


Fig. 101. Madrid MS. I, f. 17 v (detail).



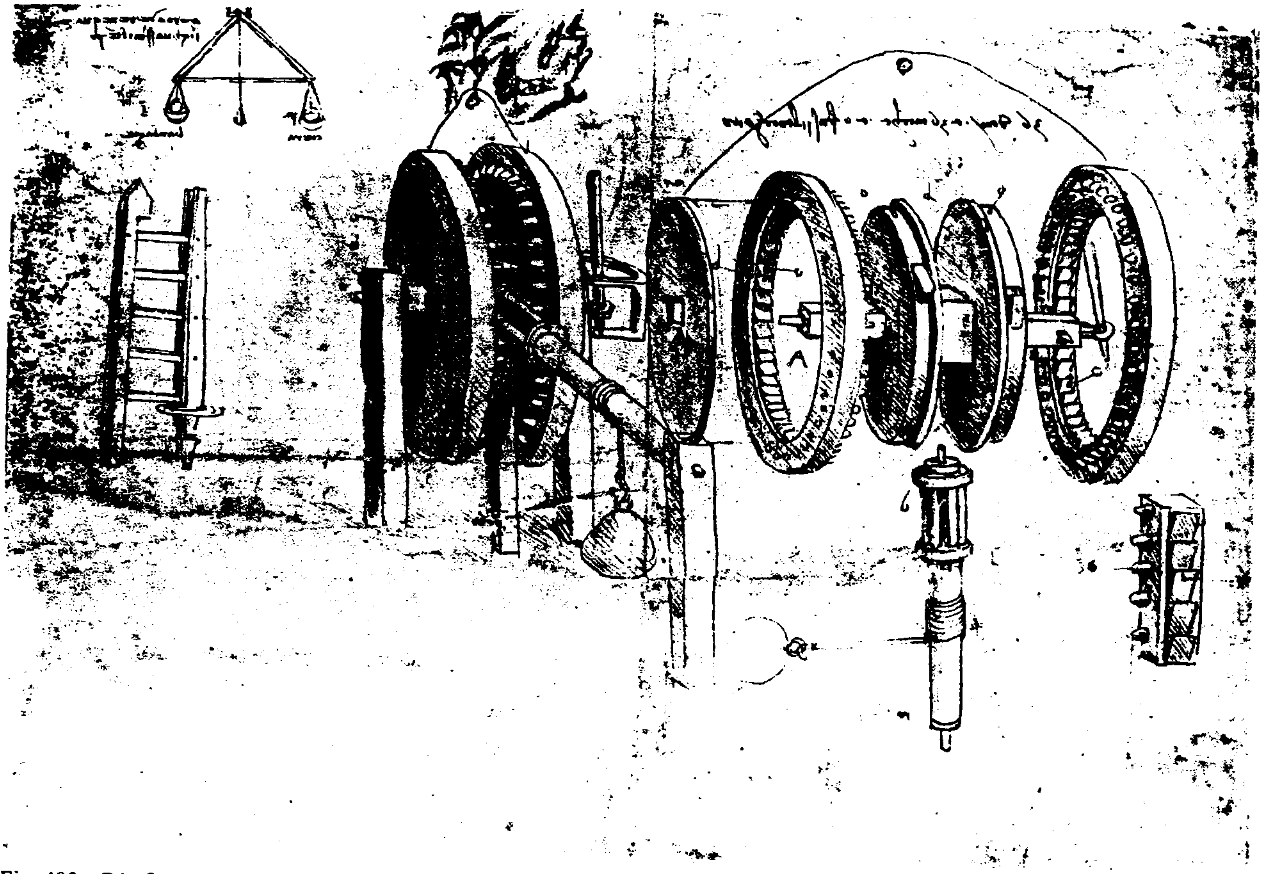
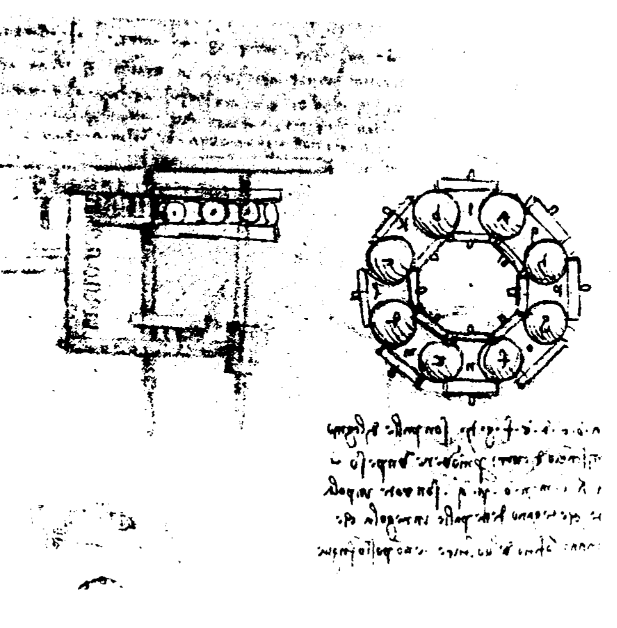


Fig. 103. CA, f. 30 v/8 v-b. General and exploded view of a hoist.

requirements shape the form of its members, which may be of infinite shapes, but all are subject to these rules of the four volumes" (Madrid MS. I, f. 96 v).

In other cases, the entire machine is presented in an exploded view (CA, f. 30 v/8 v-b: Fig. 103) to expose the complexity of the devices that ensure its smooth running.

Nevertheless, the extraordinary, almost rhetorical power of these drawings and notes, which Leonardo arranged with such care on the pages of these manuscripts, should not lead us to take for granted that these pages contain sensational discoveries. It is only with extreme caution that the invention of devices such as the ball bearing[117] (Fig. 104) or the universal joint[118] (Fig. 105) should be attributed to Leonardo. The most we can say is that we find in Madrid MS. I their first illustration.



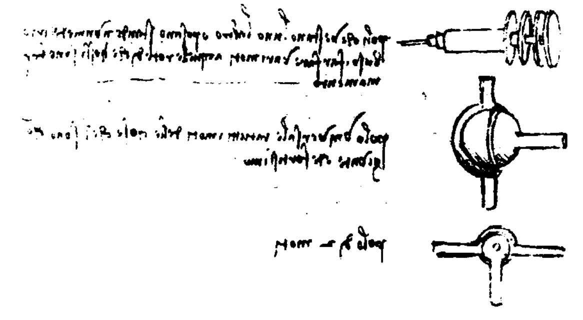


Fig. 105. Madrid MS. I, f. 100 v (detail). The universal joint is in the centre.

Leonardo's true originality lies in his approach and his "style". No one had ever attempted to insert a section so rich in details of practical applications into a treatise on mechanics. Nor had anyone before him approached mechanical applications with such a determination to derive them from general principles and subject them to rigorous quantitative analysis and geometrical schematization. Madrid MS. I bears witness to Leonardo's efforts around the 1490s to unite two mechanical traditions which until then had proceeded along substantially separate paths: on the one hand, classical and mediaeval mechanics which, with the partial exception of the "cases" of Aristotelian mechanics, had for the most part neglected practical applications; and on the other hand the mechanics practised in workshops by craftsmen who had only second-hand knowledge, or none at all, of texts on geometrical statics. At the beginning of his career Leonardo had been one of these "unlettered" craftsmen. But he made an enormous effort to train himself professionally. He came into contact with the sources of the great mechanical tradition and strove to assimilate the "elements" of geometry. Yet he never forgot his workshop training, nor the importance of *giovamenti* (practical benefits); he attempted to enlarge the boundaries of the science of mechanics to include real machines that operated with physical structures, encountered friction and obstacles in the medium, or made use of materials of limited resistance. And he always derived every investigation from general principles, subjecting every anomaly to a precise quantitative analysis.

What we should appreciate is Leonardo's attempt to redefine the science of mechanics, rather than the concrete results he obtained, which were not exceptional and which were even, at times, incorrect. This attempt corresponds to a project for the radical reformation of the profession of the engineer and clearly indicates how removed Leonardo was from so many of his admittedly able, worthy colleagues.

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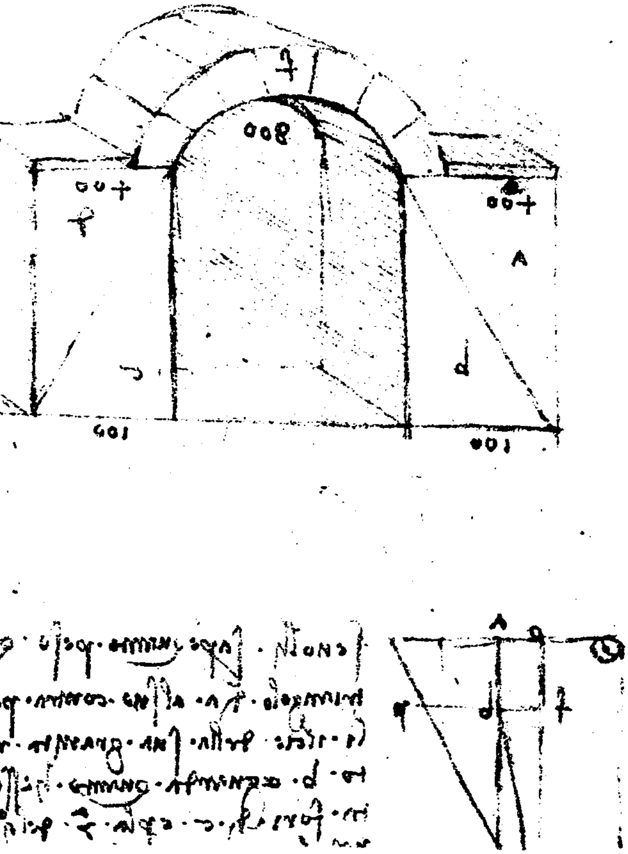
These mechanical investigations were not destined to remain an end in themselves. In the more than twenty years between the last notes and drawings in Madrid MS. I and the death of Leonardo, his "anatomy of machines" does not seem to have made great progress. And yet these investigations provided a model which Leonardo steadfastly attempted to transfer to other fields of research. It is no coincidence that references to the "mechanical elements" become more frequent in his papers after 1500. By this time, the four powers of Nature had come to be seen by him as the cause behind every effect. In addition, Leonardo strove to achieve a complete geometrical analysis, concentrating on dynamic processes and on the mechanical instruments by which they could be carried out. This method found an application in Leonardo's architectural studies, where he introduced the laws of the "mechanical elements" to account in quantitative terms for the lateral thrusts of arches (Madrid MS. I, f. 143 r: Fig. 106). He analyzed buildings and their components as if they were "machines", not merely static structures based on precise proportions, but living organisms in dynamic equilibrium. Hence the evocative analogy between the physician and the architect — a *topos* widely used by Renaissance architects which Leonardo took up, shifting the emphasis from the similarities between the human body and buildings, to the mechanical knowledge necessary to understand both:

> Just as doctors... should understand what man is, what life is, what health is... and with a good knowledge of the things mentioned above, he will be better able to repair than one without it... The same is necessary for an invalid building, that is a doctor-architect who has a good knowledge of what a building is, and



ladrid MS. I, f. 143 r (detail).

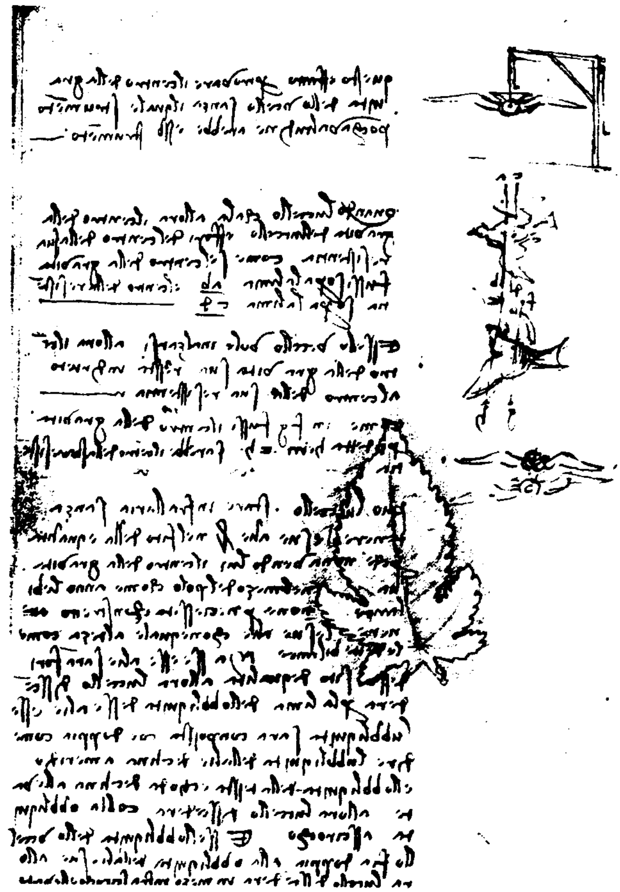


Fig. 107. Codex on the Flight of Birds, f. 15 v (detail).

from which rules good building derives, and the origin of those rules and into how many parts they are divided and what are the causes that keep a building together and make it last and what is the nature of the weight and the thrust of the force... (CA, f. 730 r/270 r–v).

Even the earth appeared to Leonardo as a huge living, breathing organism traversed by a constant circulation of humours, where every ebb and flow, every rise or fall of water follows mechanical laws. In the animal world, his study of the bird-machine revealed the mechanical secrets governing the marvel of flight, which Leonardo often referred to as "balancing in the air", while he compared the action of wings to that of a wedge:

The hand of the wing is what causes the impetus; and then the elbow is held edgewise in order not to check the movement which creates the impetus; and when this impetus is afterwards created, the elbow is lowered and set slantwise and in slanting it makes the air upon which it rests almost into the form of a wedge, upon which the wing raises itself... (Codex on the Flight of Birds, f. 15 v: Fig. 107).

After 1500, man became Leonardo's preferred field of mechanical investigation. Under the significant influence of Ptolemy's cosmography, Leonardo outlined his own programme for a universal mechanical geography, a new, amply illustrated encyclopaedia based upon a limited number of fundamental mechanical principles and on rigorous geometrical analysis. Leonardo radically transformed the encyclopaedic idea of the Renaissance. He no longer saw it as a system of universal correspondences and harmony of proportions, but as a unity of processes and functions, a unity based on motion, with constant mechanical laws and models for every type of organism: machines, buildings, the earth, animals, and man. Obviously, man occupied a prominent place in this ambitious project, and Leonardo devoted many of his most striking drawings and writings to the description of the marvellous human machine.

In the extraordinary series of anatomical drawings from the first decade of the 1500s, Leonardo's mechanical approach, influenced by the model of the "mechanical elements", becomes strikingly evident. In essence, Leonardo's study of human anatomy appears to a great extent to be an offshoot of his study of the "anatomy" of machines, which preceded his anatomical studies both conceptually and chronologically.[119] Leonardo's studies of human anatomy are indebted to his mechanical investigations not only for their general physical principles, but also for certain characteristic features of vocabulary, techniques of illustration, and several striking analogies. The corpus of Leonardo's anatomical studies at Windsor abounds in explicit statements about their dependence on mechanical models:

> Arrange it so that the book on the mechanical elements with its practice precedes the demonstration of the movement and force of man and of other animals, and by means of these you will be able to prove all of your propositions (RL 19009 r; K/P 143 r).

And again, in a note with the heading "On machines":

> Why Nature cannot give movement to animals without mechanical instruments, as I demonstrate in this book, in the active movements made by Nature in animals; and for this reason I have drawn up the rules of the four powers of Nature, without which Nature cannot give local motion to these animals (RL 19060 r; K/P 153 r).

Leonardo's anatomical investigations present the human body as a remarkable ensemble of mechanical devices:

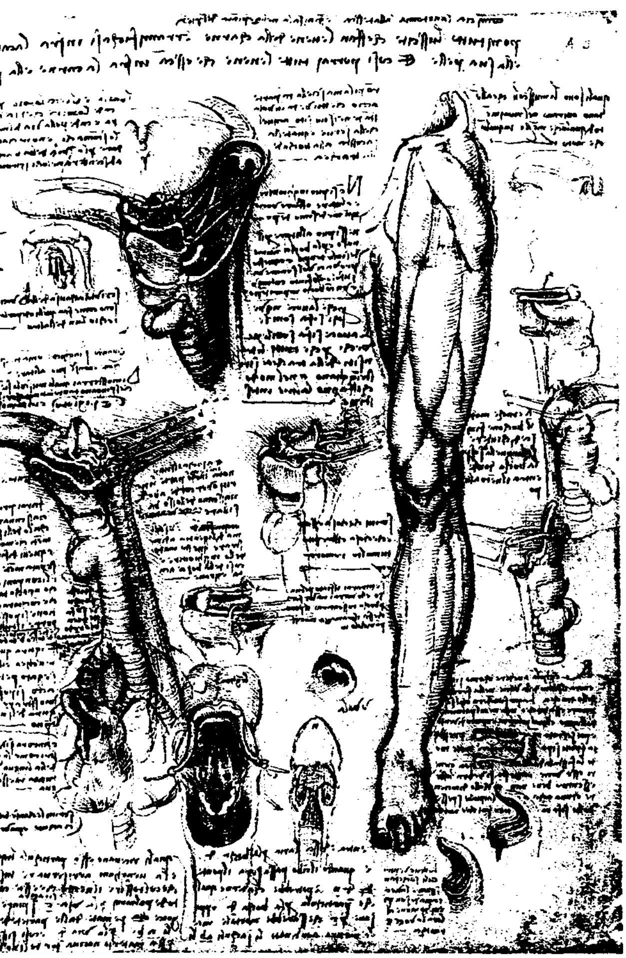
> It does not seem to me that coarse men with lewd habits and little reasoning power deserve so beautiful an instrument or so many varieties of mechanism [*machinamenti*]... (RL 19038 v; K/P 80 v).

He continually stresses the necessity to look beneath the "armatures" of the human body, exactly as he had suggested doing with machines: "Break the jaw from the side, so you can see the uvula" (RL 19002 r; K/P 134 r: Fig. 108); and "I want to remove that part of the bone which is the armature of the cheek... to reveal the breadth and depth of the two cavities that are hidden behind it" (RL 19057 v; K/P 43 v).

In these drawings the articulations of the human body are presented as revolving axles (*poli*). In the notes and the beautiful drawings on a Windsor sheet (RL 19005 v; K/P 141 v: Fig. 109) the shoulder joint is analyzed in exactly the same way as the universal joint or "*polo*" is in Madrid MS. I (f. 100 v). Again, the term "*polo*" is systematically used to indicate the axis of rotation of the ankle in a passage which stresses the analogy between the constituent organs of the human body and mechanical devices:

> The fulcrum [*polo*] *a* is the one where a man balances his weight through the tendons *m n* and *o p*, which are to the shank of the leg above the said fulcrum what the shrouds are to the masts of ships (RL 19144 r K/P 102 r).

Here we find the mechanical analogy of the mast of a ship, with its supporting stays, which Leonardo would later use extensively in his magnificent studies of the spinal column (RL 19049 r and



g. 108. RL 19002 r; K/P 134 r.

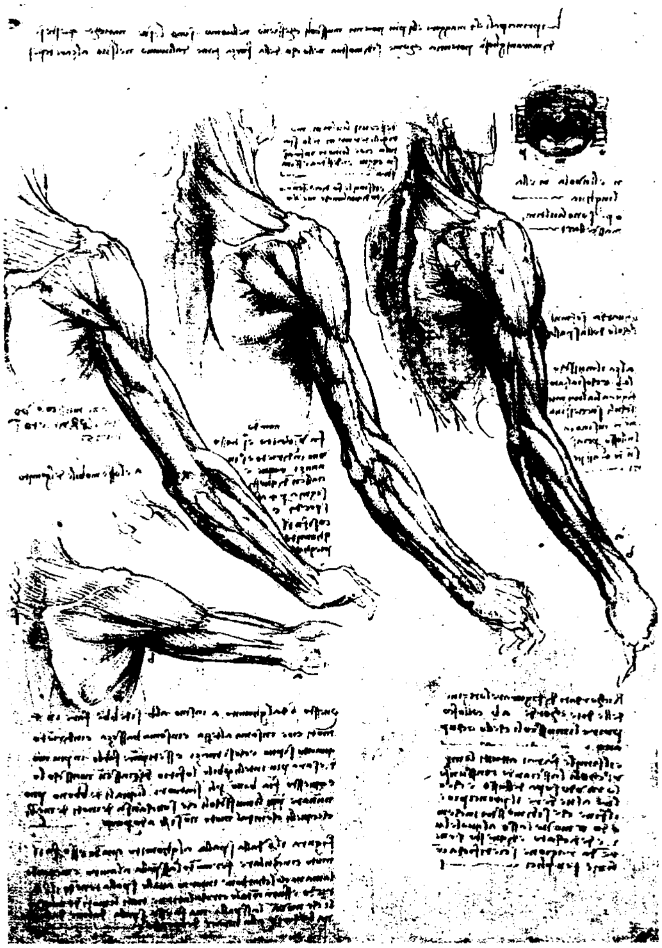
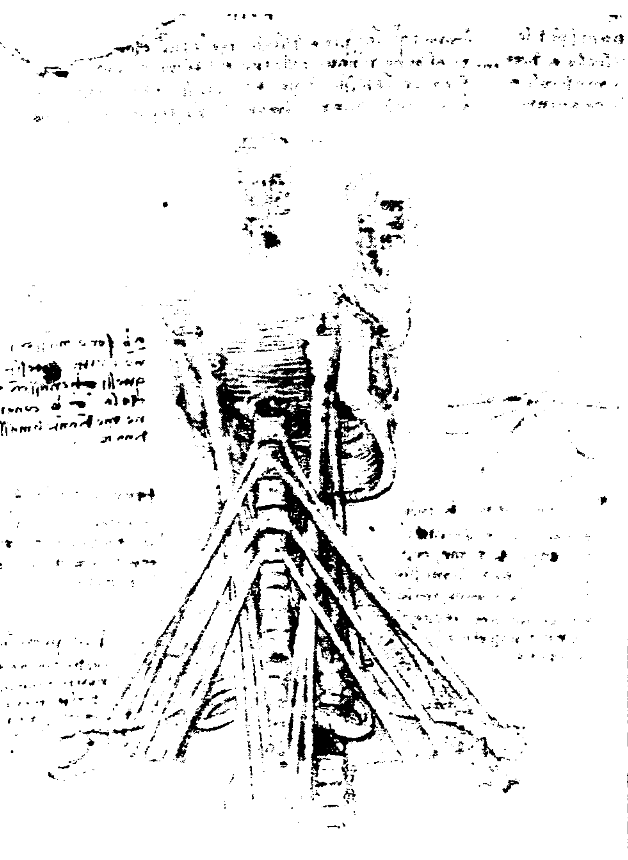


Fig. 109. RL 19005 v; K/P 141 v. Studies of the shoulder.



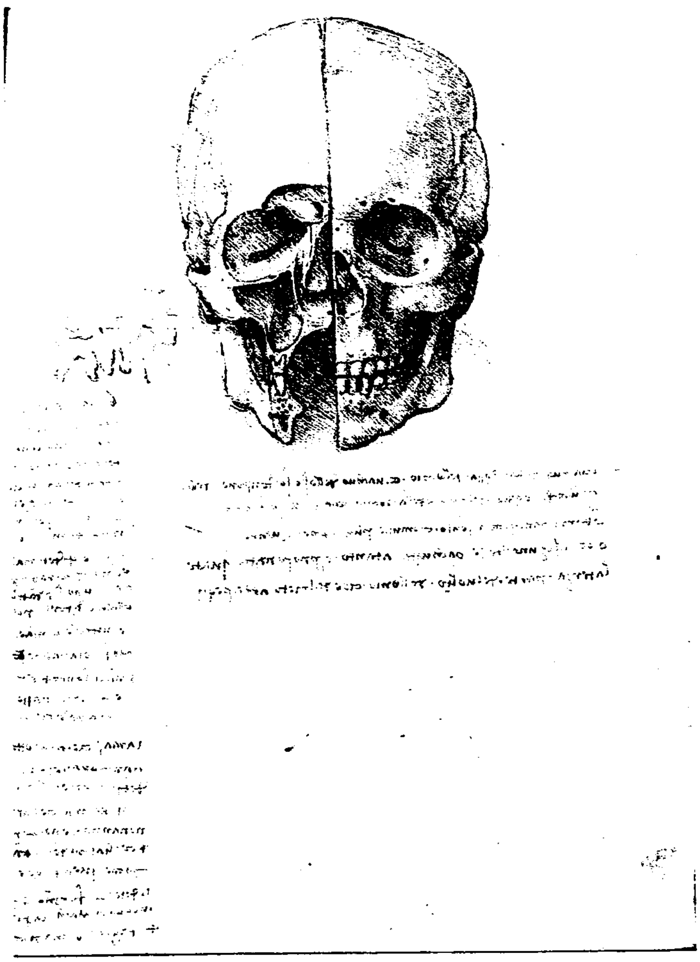


Fig. 112. RL 19058 v; K/P 42 v.

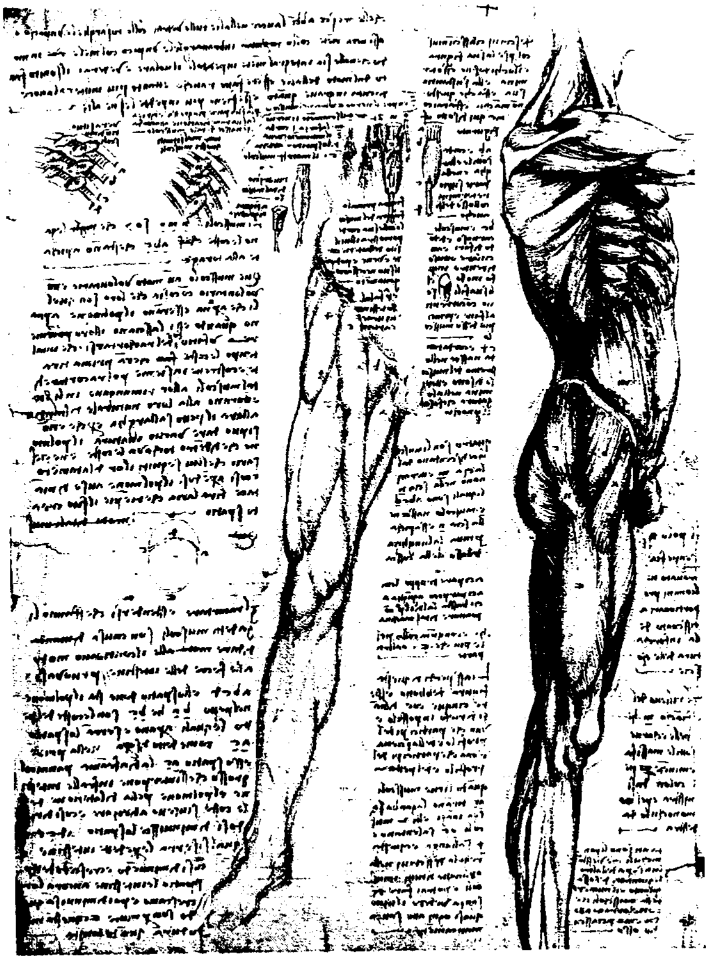


Fig. 113. RL 19014 v; K/P 148 v.

19075 v; K/P 58 r and 179 v: Fig. 110). As in the treatise on mechanical elements, the study of joints and *poli* led Leonardo to look for anti-friction mechanisms in the human body, which he found in the "glandular bones":

> Nature has placed the glandular bone under the joint of the great toe of the foot because if the tendon to which this sesamoid bone is joined were without the sesamoid, it would receive great damage in the friction made under so great a weight (RL 19000 r; K/P 135 r: Fig. 111).

Leonardo frequently compared the action of the muscles to a "wedge" (RL 19020 v; K/P 57 v). Moreover, he habitually rendered muscles as lines of force, calling them "powers" (*potenze*). Finally, he regularly used the terms "lever" and "counterlever" to explain the various motions of the upper and lower limbs (RL 19009 r; K/P 140 r).

Further evidence attests to the fact that the "mechanical elements" provided a clear model for Leonardo's analysis of the human machine. In fact, he examined individually many of the devices and mechanisms of the human body using the technique he had tested in Madrid MS. I. This approach is evident in the drawings of single teeth (RL 19058 v; K/P 42 v: Fig. 112), where Leonardo derives their respective shapes and functions from their mechanical actions. This is also true of a significant group of drawings of various components of the man-machine: nerves, sinews, veins, arteries, and muscles — each one associated with a specific function (RL 19014 v; K/P 148 v: Fig. 113). Finally, Leonardo often resorted to geometrical schematizations of the functions of organs in order to illustrate the mechanical laws on which they depend, as in the actions of the intercostal muscles (RL 19061 v and 19015 v; K/P 154 v and 149 v: Fig. 114), or in the comparison of the motions of the jaw to those of a lever (Fig. 115), where the related texts display the characteristic conciseness of the propositions of the traditional texts on geometrical statics:

> That tooth has less power in its bite which is more distant from the centre of its movement (RL 19041 r; K/P 44 r).

The mechanical geography of man, the "lesser world", also offers striking analogies with the "mechanical elements" in terms of the role played by drawing. The complexity of the subject — man — impelled Leonardo to perfect the remarkable gifts as a technical draughtsman that he had displayed in the mechanical drawings in Madrid MS. I. The number of views is increased, exploded views are continually used, techniques of penetrating structures are refined (RL 12281 r; K/P 122 r: Fig. 116). Finally, Leonardo introduced a new technique. On a single sheet he produced drawings of successive strata of the organs he was dissecting, starting from the bare bones and ending with the skin:

> You will first draw each part of the instruments which move and define them separately, and then put them together little by little so that the whole can be composed with clear knowledge (RL 19002 r; K/P 134 r: see Fig. 108).

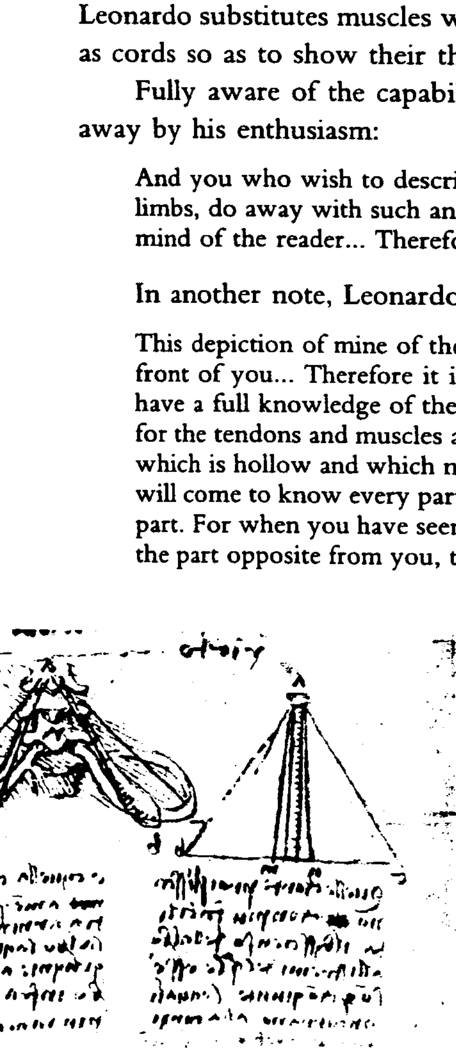
Returning to a precept he had advanced in the passage from Madrid MS. I quoted above, about removing the "armatures" of machines so they will not impede the view of the inner workings, Leonardo substitutes muscles with lines of force, recommending that they be rendered not as lines but as cords so as to show their three-dimensionality.[120]

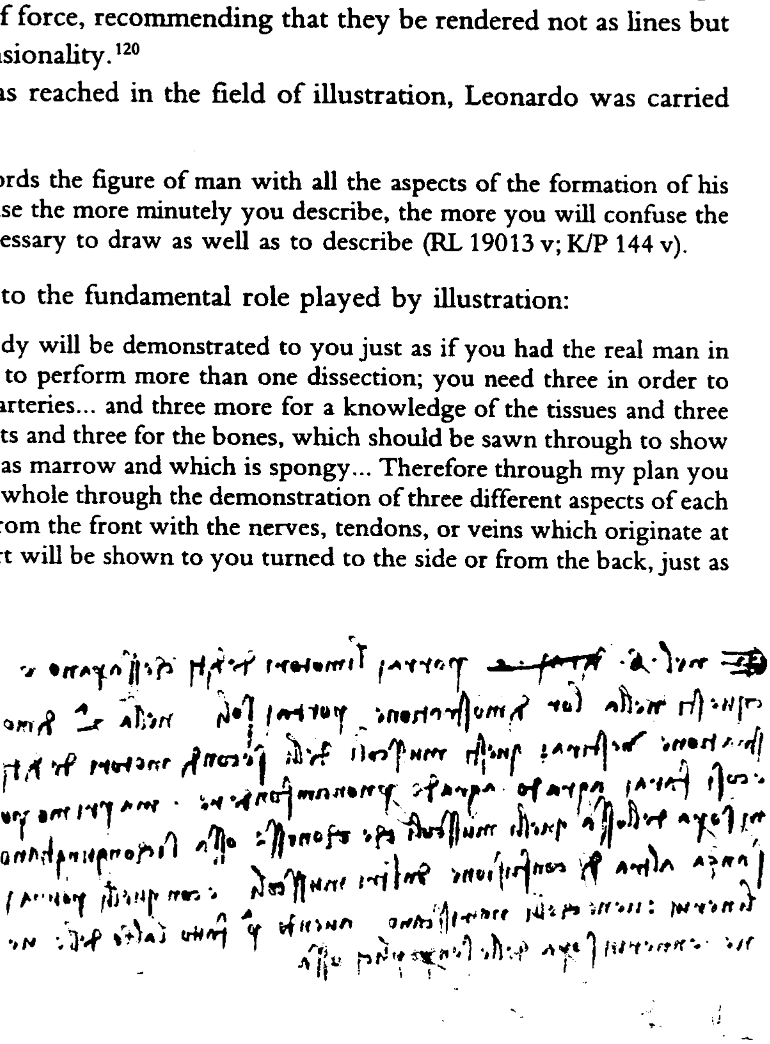
Fully aware of the capabilities he has reached in the field of illustration, Leonardo was carried away by his enthusiasm:

> And you who wish to describe with words the figure of man with all the aspects of the formation of his limbs, do away with such an idea, because the more minutely you describe, the more you will confuse the mind of the reader... Therefore it is necessary to draw as well as to describe (RL 19013 v; K/P 144 v).

In another note, Leonardo returned to the fundamental role played by illustration:

> This depiction of mine of the human body will be demonstrated to you just as if you had the real man in front of you... Therefore it is necessary to perform more than one dissection; you need three in order to have a full knowledge of the veins and arteries... and three more for a knowledge of the tissues and three for the tendons and muscles and ligaments and three for the bones, which should be sawn through to show which is hollow and which not, which has marrow and which is spongy... Therefore through my plan you will come to know every part and every whole through the demonstration of three different aspects of each part. For when you have seen any part from the front with the nerves, tendons, or veins which originate at the part opposite from you, the same part will be shown to you turned to the side or from the back, just as





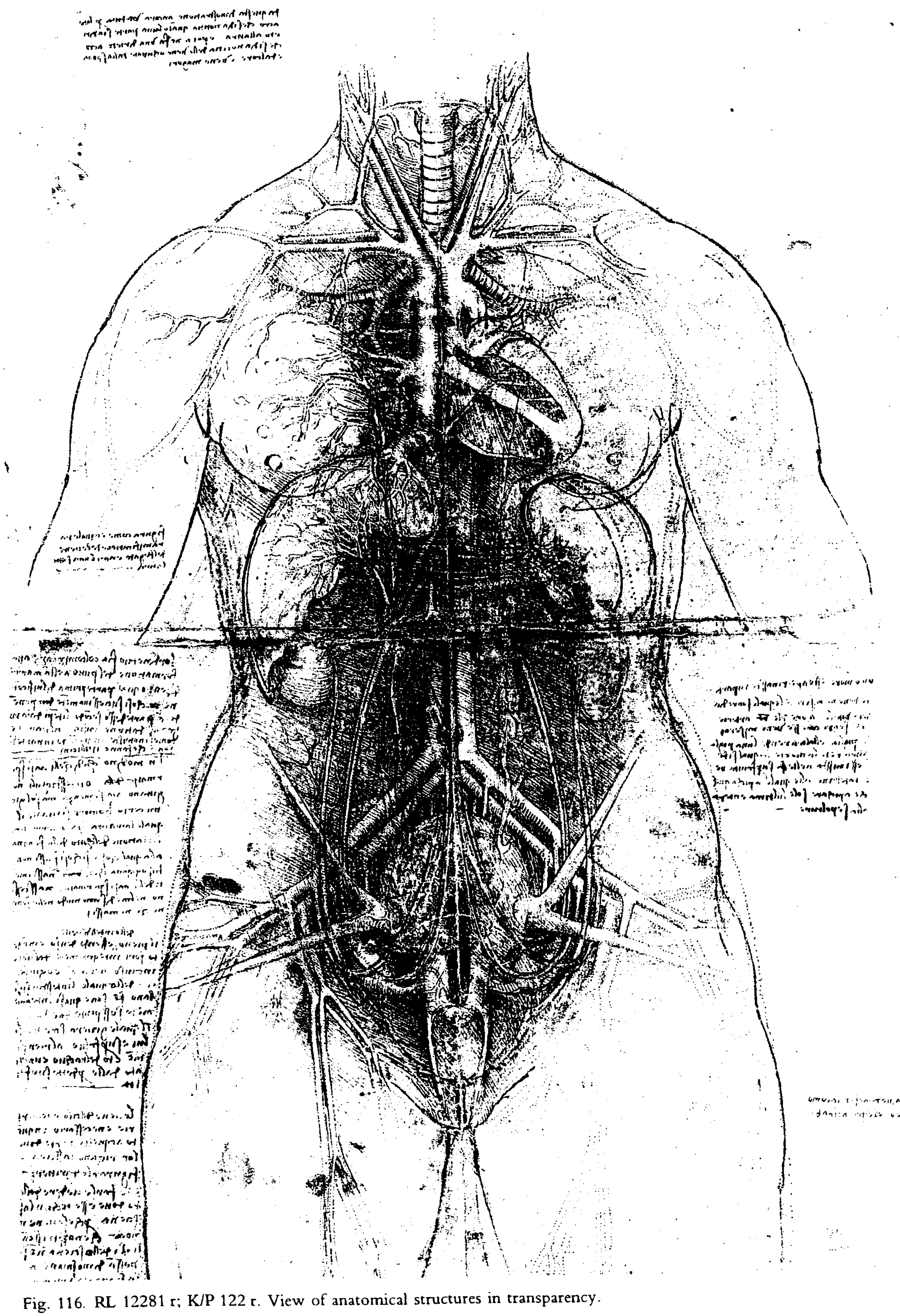


Fig. 116. RL 12281 r; K/P 122 r. View of anatomical structures in transparency.

117. RL 12619 r; K/P 152 r.

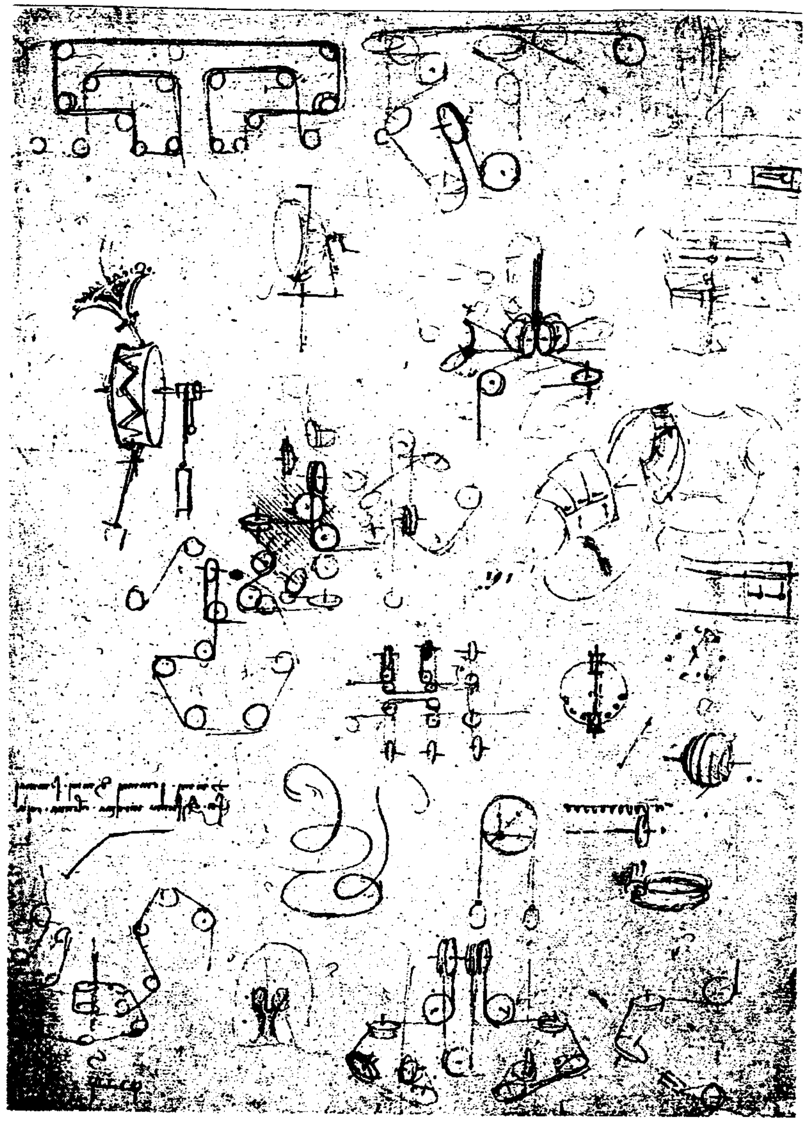


Fig. 118. CA, f. 579 r/216 v-b. Study for an automaton.

if you had that member in your hand and were turning it over from one side to the other until you had obtained full knowledge of what you want to know (RL 19061 r; K/P 154 r).

The final remark about turning the "member" over in one's hands suggests leaving the confines of a two-dimensional plane to become three-dimensional, where the perfect illustration becomes equivalent to a three-dimensional model. And Leonardo made many such models during these years, such as the one of the lower limb (RL 12619 r; K/P 152 r: Fig. 117) with the lines of force of the muscles schematically rendered as copper wires, or the ones of the eye (Paris MS. D, *c.* 1508, f. 3 v: see Fig. 2), and of the aorta (RL 19117; K/P 115 v). But Leonardo was familiar with models — as Vasari recalls — in other areas as well. He made architectural, sculptural, mechanical, and hydrodynamic models. In fact, the use of models by Leonardo is a subject that merits further attention.[121] It was the extraordinary power of the analogy between man and machine that suggested to Leonardo the use of techniques of illustration such as lines of force. This is even more true for the anatomical models that were a translation of the organ into a functioning mechanical device. Pedretti has related the project for an automaton recorded in the Codex Atlanticus (f. 579 r/216 v-b: Fig. 118) to the theme of the model.[122] It is difficult to say whether this can be considered the ultimate outcome of Leonardo's rigorously mechanistic approach to the study of the human body. More than a century after Leonardo, Descartes' equally rigorous mechanistic approach, albeit totally different in methods and principles, was to inspire some extraordinary mechanical realizations that effectively reproduced human functions and movements.

There remains the coherence with which, with the anatomy of machines as his point of departure, for more than a decade Leonardo carried out an analysis of the human body that was based on direct observations and yet was strongly conditioned by a rigid interpretation which, at a certain point, he was tempted to extend (as indeed Descartes was to do) to the analysis of human passions:

> And would that it might so please our Creator that I were able to demonstrate the nature of man and his customs in the way that I describe his shape (RL 19061 r; K/P 154 r).

However, here and there in the tight fabric of Leonardo's mechanistic conception some dangerous cracks appear through which the awareness of an irreducible distinction between machines and man tries to break out:

> Although human ingenuity in various inventions with different instruments yields the same end, it will never devise an invention either more beautiful, easier, or more rapidly than does Nature, because in her inventions nothing is lacking and nothing is superfluous, and *she does not use counterweights* [my italics] but places there the soul, the composer of the body... (RL 19115 R; K/P 114 r).

This passage seems written purposely to contrast the human body with the automaton, that is, to oppose natural creatures to artificial devices. But Leonardo reacts violently to this, adding a disdainful note to his own text:

> This discussion does not belong here, but is required in the composition of the bodies of animals. And the rest of the definition I leave to the minds of the friars, fathers of the people, who by inspiration know all secrets (RL 19115 r; K/P 114 r).

It was precisely when confronted with a difficulty which seemed to shake the very foundations of his tenaciously pursued plan of unification that Leonardo once again stressed the validity of an investigation of man according to rigorously mechanical guidelines. And it was an effective way for him to emphasize once more that the engineer and the physician, like the artist and the architect, used methods and skills that were essentially the same, based on the same set of principles derived from the diligent imitation of Nature.