LEONARDO DA VINCI
Engineer and Architect

The Montreal Museum of Fine Arts

I.2

*Leonardo's Impossible Machines**

by
Augusto Marinoni

In the famous letter in which he offers his services to the Milanese duke Lodovico Sforza, called Il Moro, Leonardo dwells at some length on his abilities in the field of military engineering. It is only in the closing lines of the letter that he speaks of the value, even "in time of peace", of his talents as a civil engineer, an architect, and a sculptor well qualified to execute the equestrian monument to be dedicated to the memory of Lodovico's father, Francesco Sforza. In a subsequent letter, however, addressed to the churchwardens of the Cathedral of Piacenza, Leonardo states that he has been summoned to Milan to build the equestrian monument but adds, rather gloomily, that it is such a major undertaking that he doubts he will ever finish it — a remark illustrative of a state of mind to which Leonardo was frequently subject. In fact, the great attraction that unusual projects held for him and the doubts engendered by the unattainability of perfection — a source of dissatisfaction even in relation to his most admired masterpieces — combined to nourish an unconquerable sense of self-criticism which, all too often, was the cause of abandoned and uncompleted work.

Leonardo remained in the service of the Sforzas for seventeen years. During this period he modelled in clay a gigantic horse, which was undoubtedly magnificent, but which was never actually cast in bronze. Some scholars believe this to have been the result of insuperable technical difficulties; others assume there was simply a shortage of the necessary metal, which was used exclusively in the manufacture of cannons. They all seem to forget that the duke wanted more than a horse without a rider.

Before examining some of the various machines designed by Leonardo, it seems worthwhile to

* The aim of this essay is to highlight one of the characteristic facets of Leonardo's technology, through an examination of a group of projects considered to be impracticable, or, at least, considerably ahead of their time. The introductory section deals with several commissions given to Leonardo in his capacity as a "military engineer". But there is also a large number of drawings of weapons and fortifications that bear witness to intense research and possibly even represent preparations for specific practical projects, although the significance — and even the existence — of such projects remains doubtful and undocumented. On the subject of fortifications, the reader is advised to consult a recently published work by Marani, 1984[2]. As far as the machines are concerned, we will mention only a few of the many works published on the subject.

recall the main points of his activity as a military engineer. It has often been repeated that while in Milan, Leonardo also fulfilled certain military duties, but the nature and extent of these have never been clearly defined. The ducal administration had at its disposal excellent, very active engineers whose energies were devoted entirely to military questions. Nevertheless, Leonardo's manuscripts contain numerous studies of fortifications, offensive weapons and instruments of defence of all kinds, and it is yet to be decided just how these should be classified: were they exercises in pure research, or were they created in response to particular orders? Several pages of his earliest manuscript — Paris MS. B — contain extremely detailed descriptions of ancient weapons copied from Valturius' *De re militari* and frequently accompanied by quotations from classical authors. These sheets represent a short-lived attempt on Leonardo's part to adapt to the humanist customs of his contemporaries. The Codex Atlanticus, on the other hand, includes an extensive series of weapons designed by Leonardo himself and drawn with the greatest of care, as if the sketches were to be presented to a prospective manufacturer. Milan, at that time, was home to various highly reputed factories well equipped to construct the war machines invented by Leonardo; nothing, however, indicates that they actually did so. Whatever the case, the aesthetic value and originality of these inventions were no doubt less appreciated than their practical and economic qualities.

The magnificent drawing on folio 1070 r/387 r-a of the Codex Atlanticus is an example from this series. It shows a huge wheel, approximately four metres in diameter. The outer surface consists of a series of steps which are being scaled by a group of men whose weight sets the wheel in motion. The whole is protected by a sturdy defence structure containing a loophole. Attached to the four spokes are four crossbows loaded with large, heavy arrows. When a crossbow falls in line with the loophole, the wheel stops, a soldier activates the release mechanism and an arrow is shot towards those of the enemy within range of the fixed target. However, the large number of soldiers by which this machine was to be manned would have been able, armed with ordinary bows, to select and shoot at moving targets, thus claiming far more victims than the huge machine; the device would clearly have been effective only in particular situations — for example, to keep certain clearly-defined, crucial points under heavy and constant fire during a siege. There is no proof, though, that the structure was ever built.

In 1499, when Milan fell to the French, Leonardo travelled to Venice where he was consulted by the authorities concerning ways of repelling a possible attack by the Turks. There remain only a few traces in the Codex Atlanticus of the report Leonardo submitted — unfortunately not enough to gain any real insight into his plan.

In 1502, Leonardo's skill as a military engineer was acknowledged in the highest quarters: in a letter patent, dated August 18 of that year, Cesare Borgia, Duke of Romagna, ordered his subjects to give free passage "to our excellent and beloved friend, the architect and general engineer Leonardo da Vinci... who, by our order, is to examine the towns and fortresses of our States in order that we may act taking all requirements into account and in accordance with his judgement". Leonardo had apparently already been in Cesare Borgia's service for some time; in his work *De viribus quantitatis*, Luca Pacioli tells of an episode that took place early in 1501. It seems that Cesare Borgia was obliged to cross a river at a spot where there were no bridges and, according to Pacioli, Borgia's "noble engineer" quickly found a solution to the problem by making use of a pile of tree trunks lying nearby. As the trunks were shorter than the width of the river, he placed them jutting out diagonally from both banks, their ends meeting in the middle. The other ends were firmly embedded in the earth and

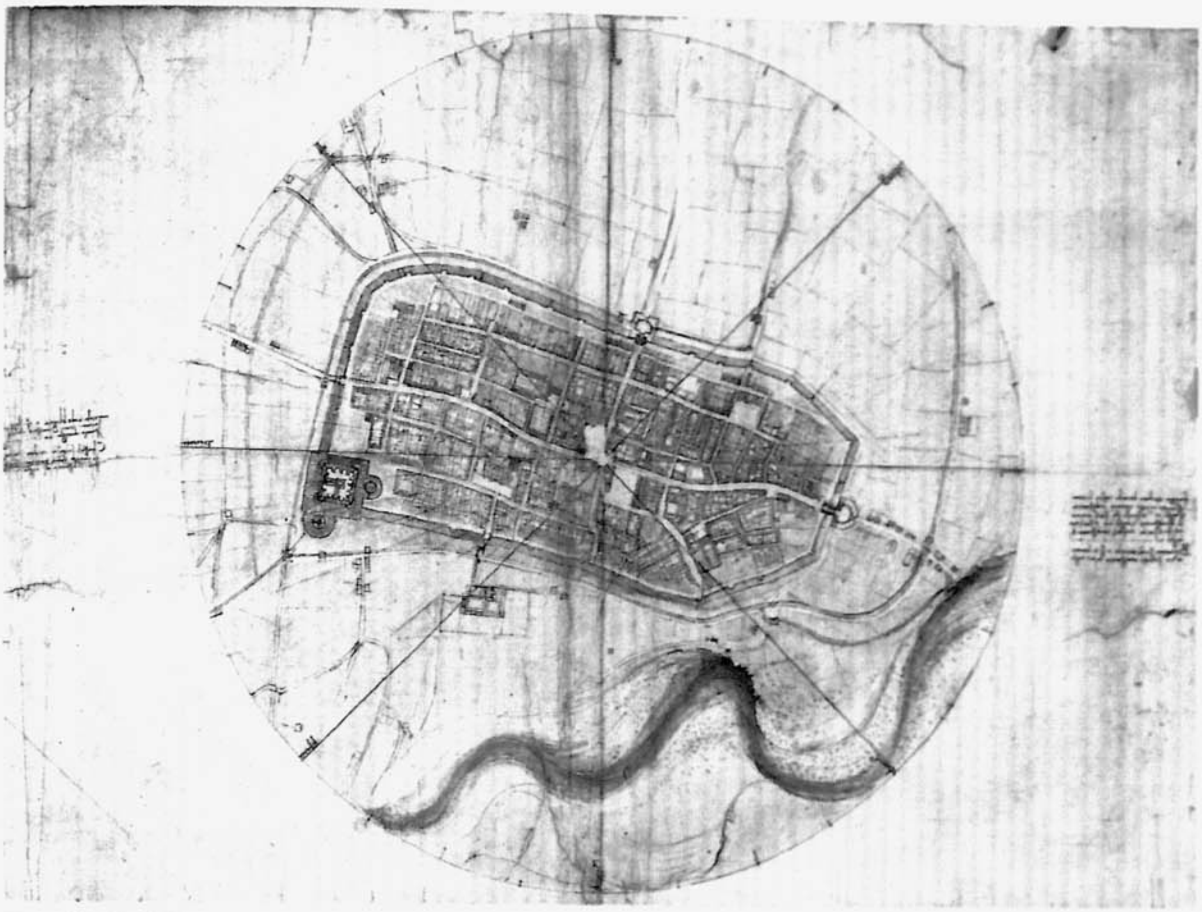

Fig. 119. RL 12284.

weighed down so as not to give way under the force of the water. This account does not mention Leonardo by name, but it seems unlikely that the adjective "noble" would have been applied to anyone other than the "excellent... architect and general engineer Leonardo da Vinci" who, furthermore, left many drawings in the Codex Atlanticus of military bridges that could be constructed extremely fast. Proof that Cesare Borgia ordered Leonardo to visit the fortresses of Romagna is provided both by the drawings in Paris MS. L and by the Windsor sheets depicting the fortified walls of Cesena and Urbino, and the famous map of Imola (Fig. 119). It should be noted, however, that a map of Imola had been drawn approximately thirty years before by another military engineer of the Sforza court. Leonardo made use of this earlier map, partially modifying it to suit new requirements.

After the death of his father, Alexander VI, in 1503, Cesare Borgia's fortunes declined. The war between Pisa and Florence broke out anew, and the Florentines embarked on a particularly difficult enterprise: the diversion of the waters of the Arno River so as to make them reach the sea without passing through Pisa. In July of the same year Leonardo was asked to examine the work already begun and to give his opinion. Although we have no definite information concerning any concrete intervention on his part, we do know, through sheet 12278 at Windsor (Fig. 120), of an extremely bold plan conceived by him, the execution of which would have actually been impossible. In order that the flow of water in the canal running between Florence and the sea remain constant (see Pl. X), even during summer droughts, Leonardo contemplated flooding the valley of Chiana by means of a dam situated to the south of Arezzo, thus forcing the Tiber to run into Lake Trasimeno through a tunnel.[1*]

* The notes of chapter I.2 are on page 319.

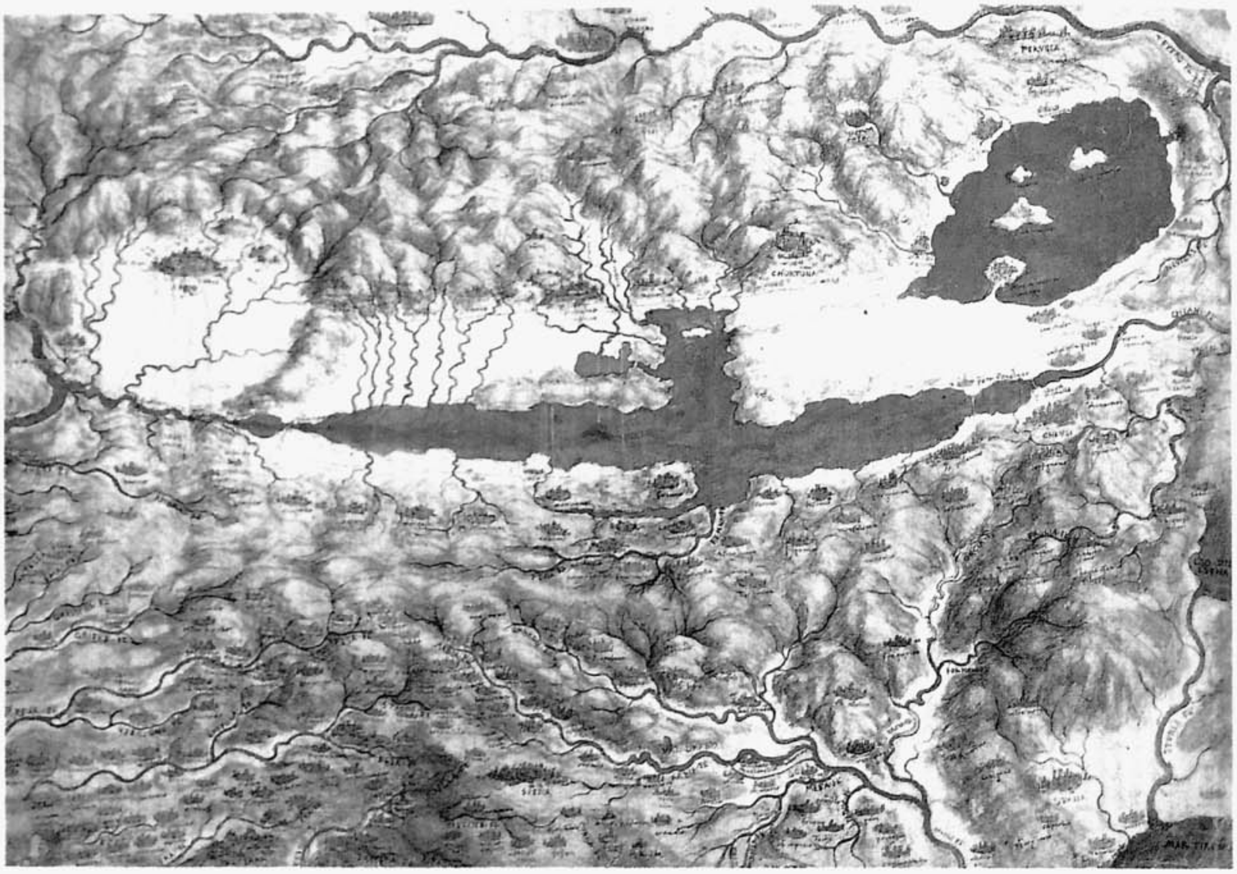

Fig. 120. RL 12278 r.

Unfortunately, Leonardo's hydrographical and orographical knowledge of the area was incomplete, and he was unaware that the Tiber lies at a lower altitude (164 metres) than the lake (258 metres). Fascinated by the daring grandiosity of the scheme, he allowed himself to dream of a fundamental transformation of geographical reality.

In 1506, back in Milan, Leonardo became friendly with the French — the new rulers of the duchy. Indeed, according to Edmondo Solmi,[2] he apparently participated to a certain extent in the preparations for the war against Venice on which Louis XII was about to embark. Evidence for this is said to be provided by certain sketches on Windsor sheets 12673 r (Fig. 121) and 12674 r (Fig. 122), which are maps of the hydrographic systems of the Bergamo and Brescia valley regions. Baratta, on the other hand, interprets these sketches as a hydraulic development, possibly involving a canal between the Adda River and Lake Iseo. Both these hypotheses remain, however, conjectural and unfounded.

One thing that seems certain is that around 1510 Leonardo was occupied with a non-military hydraulic problem that had concerned the people of Milan for some time. Several centuries earlier, Milan had been linked to Lake Maggiore by a navigable waterway — the Naviglio — which made possible the barge transportation of marble from the Toce valley directly to the site of the cathedral. By 1510, the lengthy construction of this edifice was nearly complete. A similar project had been proposed that would join Milan to the Lake of Lecco, thus opening the Valtellina area to the markets of Germany. By 1471, the Milanese had already built the Martesana canal as far as the Adda; the navigability of this river was hampered, however, by the narrowing at the Tre Corni. After studying

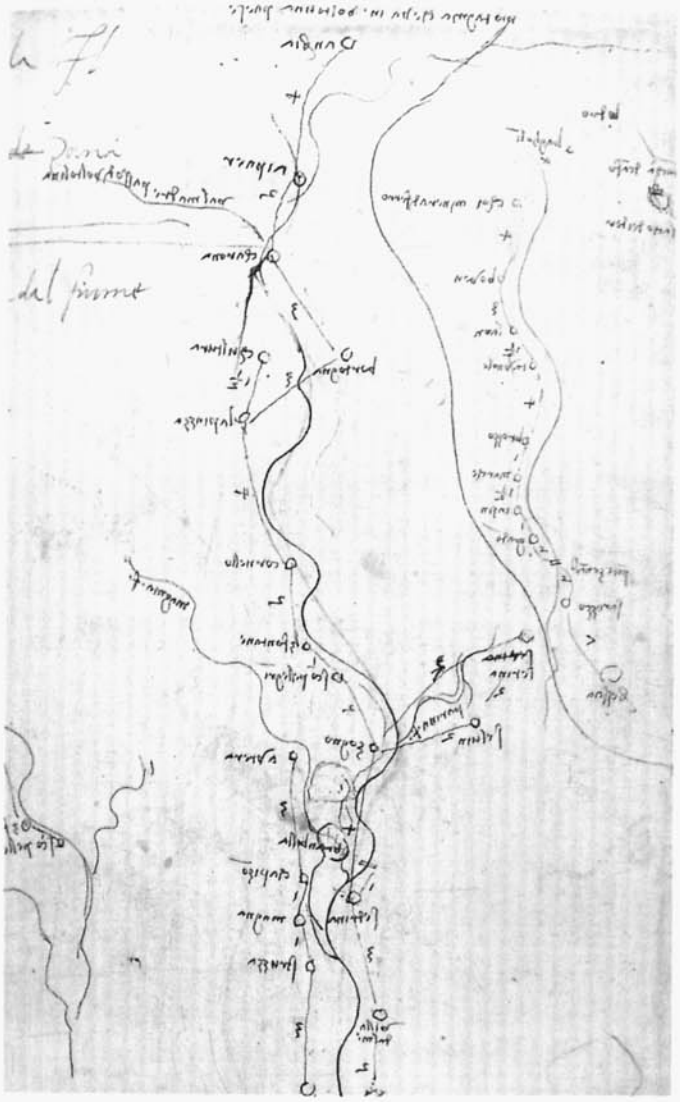

Fig. 121. RL 12673 r. (detail).

Fig. 122. RL 12674 r.

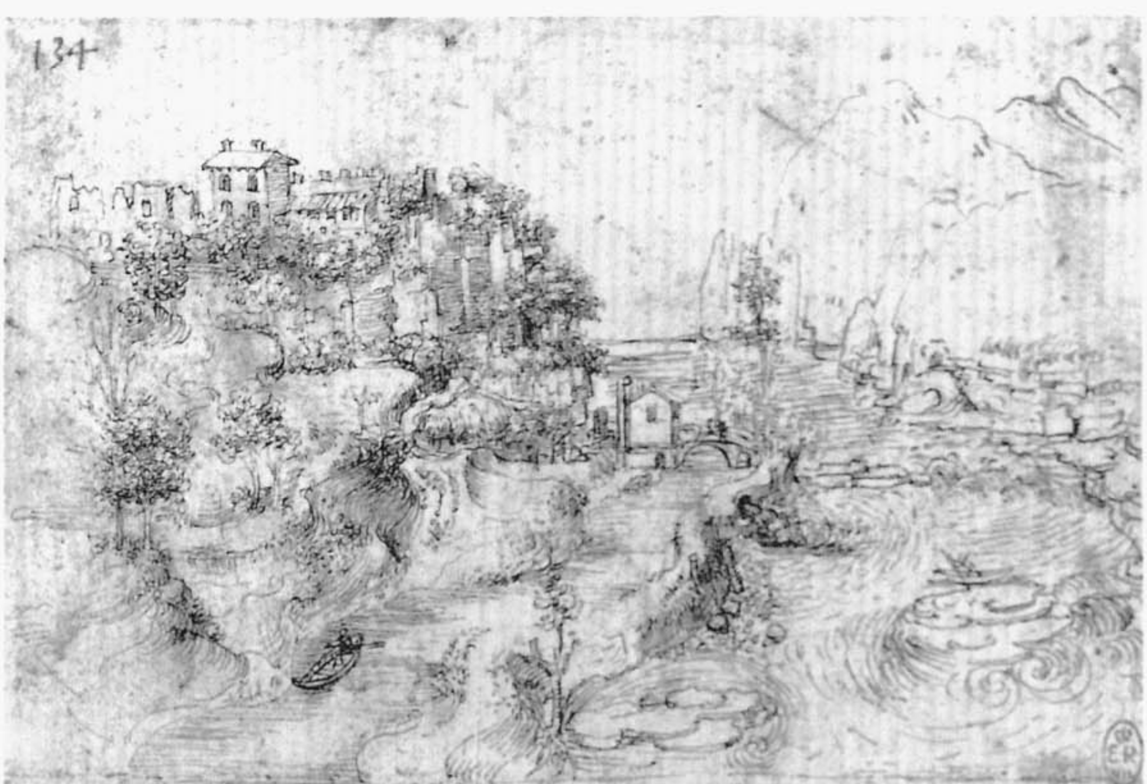

Fig. 123. RL 12399.

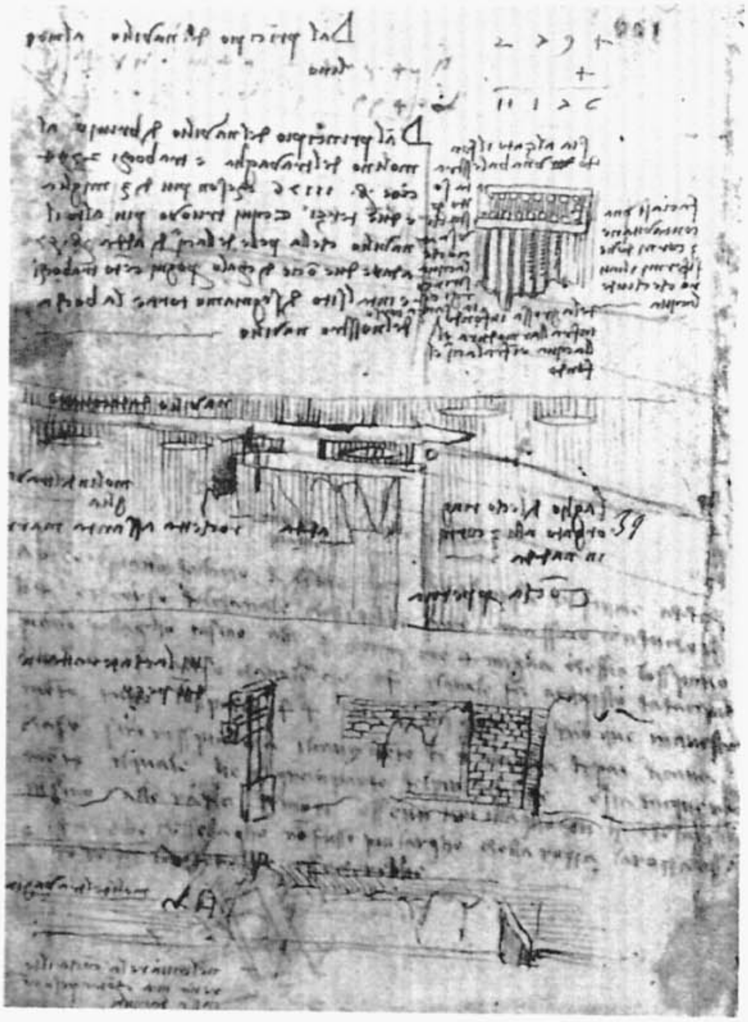

Fig. 124. CA, f. 388 v/141 v-b.

Fig. 125. CA, f. 911 r/335 r-a.

Fig. 126. CA, f. 642 Ar/236 r-b.

the feasibility of a new canal between the Lake of Lecco and the Lambro River, which would cross the Brianza lakes, Leonardo concentrated his efforts on the possibility of overcoming the obstacle of the Tre Corni (Fig. 123). Folios 388 v/141 v-b (Fig. 124) and 911 r/335 r-a (Fig. 125) of the Codex Atlanticus provide a reasonably clear idea of Leonardo's plan. His solution, which involved the construction of a dam, a lock and a tunnel, was an ambitious one that was not to be allowed to pass unnoticed by posterity. "At the mouth of the canal, at Brivio" wrote Leonardo (on CA, f. 642 Ar/236 r-b: Fig. 126), "there should be a commemorative plaque". But the plan — like many similar ones conceived in France toward the end of Leonardo's life — was destined never to be realized.

We have chosen to begin with a discussion of Leonardo's activity as a military engineer for two reasons: firstly, because it was in this capacity that he introduced himself in his letter to Lodovico Sforza and, secondly, because the military projects attributed to him by experts, although few, are well documented. His role in these endeavours seems nonetheless to have been exclusively consultative. The only reference we have to Leonardo being directly engaged in a military operation is the episode recounted by Luca Pacioli. His involvement in the war between Florence and Pisa went no further than the abortive attempt to build a canal linking Florence directly to the sea, the importance of which it is impossible to evaluate. Finally, the theory that he participated in the French war against Venice is extremely vague. As a result of the considerable space devoted to rivers and waterways throughout Leonardo's writings, many scholars have undoubtedly overestimated his activity as a builder of locks and canals. These references represent, for the most part, comparative studies of movement in a fluid medium as opposed to a solid one (mechanics). The Milanese were heirs to a centuries-old tradition of canal building, and Leonardo, once established in Milan, had far more to learn from the highly experienced Lombard engineers than he had to teach them.

We must be careful, however, not to minimize the extent of Leonardo's interest in the study, invention and development of machines. It is not possible to examine here all of his many drawings

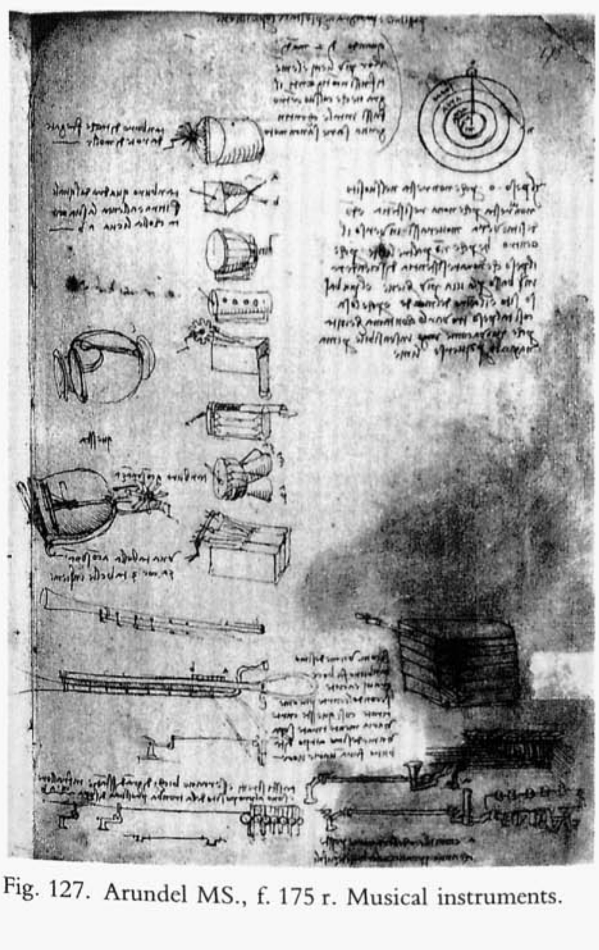

Fig. 127. Arundel MS., f. 175 r. Musical instruments.

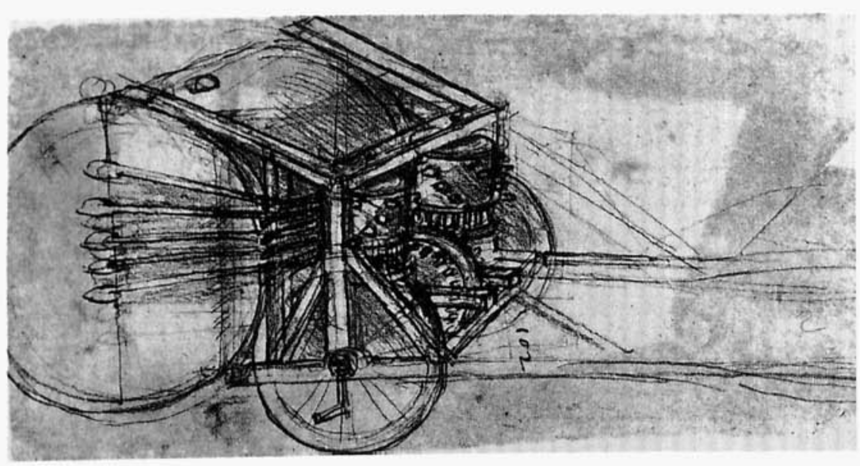

Fig. 128. CA, f. 837 r/306 v-a. Automatic drum.

depicting mechanisms of all sorts — including excavators, looms, chains, hoists, ventilators, musical instruments (Figs 127-128), swing bridges, cranes, lathes, presses, and so on — nor to investigate his research into automation. It is true that at a time when knowledge of mediaeval technology was very slight, certain ideas were attributed to Leonardo that were not, in fact, absolutely new. During the Middle Ages and in classical times, engineers were often illiterate and generally chose to execute their projects in the strictest secrecy. Libraries in Munich, Florence and London nonetheless possess fifteenth-century manuscripts that include numerous drawing of instruments that are strikingly similar to certain of Leonardo's best-known drawings. These sketches illustrate, among other things, underwater excavations (Fig. 129), paddle boats (Fig. 130) and diving suits (Fig. 131 and Pl. VI). Owing to their lack of mechanical detail, however, and the resulting doubt as to their capacity to function, they are distinctly inferior to Leonardo's designs. The parachute by an anonymous author that appears in a manuscript in the British Library (Add. 34113, f. 189 v) is clearly a work of the purest imagination, as is another illustrated a few pages further on (f. 200 v: Fig. 132). The latter is in the form of a cone and has a totally inadequate braking surface. Admittedly, Leonardo's own parachute — despite being somewhat larger — is not operable either. But what emerges from a comparison between Leonardo's machines and those of his predecessors is the remarkable development in the treatment of mechanical detail. Leonardo was heir to the dreams of Taccola, Fontana, Guido da Vigevano, and many other, anonymous, inventors; but he replaced their crude sketches with more convincing images — images that had moved out of the realm of fantasy and into the realm of potential realization.

It is important to recall here the significance of a Leonardo innovation brought to light only recently by one of the Madrid Manuscripts, which were discovered in 1966 and published in 1974, but which remain relatively little known. Madrid MS. I is a genuine treatise, if such a term can be applied to the unique type of document produced by Leonardo. The work is divided into two parts: the second section is devoted to theoretical research into the laws governing movement, or the science of mechanics; the first, though, is given over to the detailed study of individual mechanisms. As Ladislao Reti[3] has noted, apart from one absence (the bolt) and three additions, this treatise examines and describes all the mechanisms that appear on the list drawn up by Reuleaux in the late eighteenth century. When designing machines, engineers working prior to Leonardo were obliged to draw all the separate components every time. Leonardo, by contrast, studied each mechanism individually and then

Fig. 129. Additional MS. 34113, f. 72 v, British Library, London.

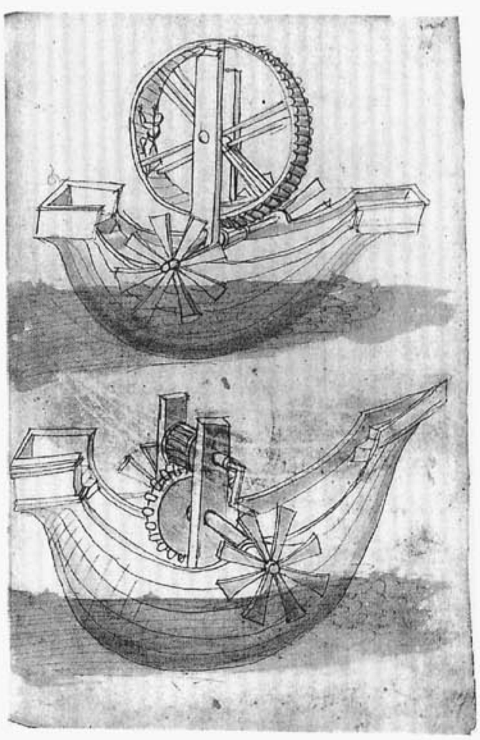

Fig. 130. Additional MS. 34113, f. 116 r, British Library, London.

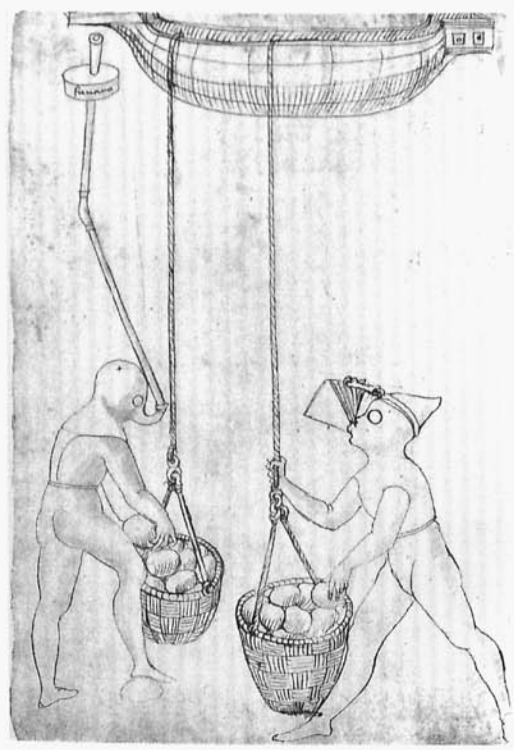

Fig. 131. Additional MS. 34113, f. 180 v, British Library, London.

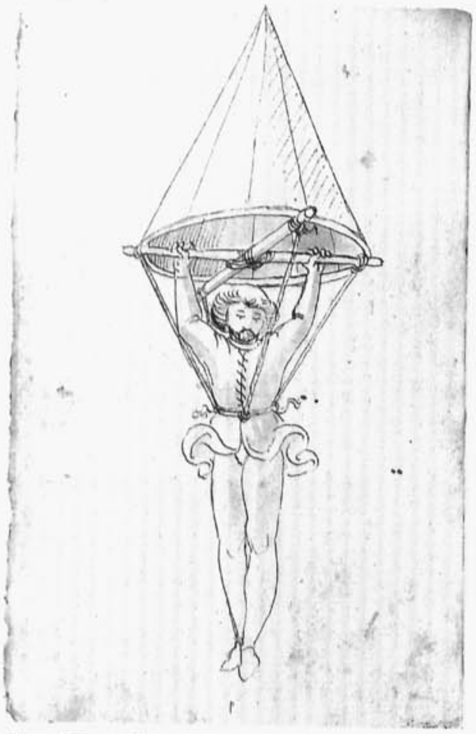

Fig. 132. Additional MS. 34113, f. 200 v, British Library, London.

employed them many times over in a broad variety of machines. In folio 82 r of Madrid MS. I, he states quite specifically: "Here we shall discuss the nature of the screw and of its lever... and how it has more power when it is simple and not double...". Clearly, the object of his study was not a particular machine, but the screw itself — its many forms and properties, and the method of its fabrication. Nor did he restrict himself to the screw, but also examined the "endless screw" and the "ratchet wheel... the flywheel... hoists, pulleys, winches, rollers" and so on. The science of mechanisms came into being in 1794, with the foundation of the École polytechnique in Paris, but its principles had already been presaged by the work of Leonardo. It is his meticulous analysis of each mechanism that renders Leonardo's machine designs more concrete and more functional (or more nearly functional) than those of his predecessors. But just how well would they actually work?

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Let us examine first of all a few of Leonardo's most extravagant schemes. Folio 83 v/30 v-a of the Codex Atlanticus illustrates a device consisting of twenty-four revolving shafts (Fig. 133) arranged horizontally and connected by cogwheels in such a way that one complete revolution of the first shaft would give rise to twenty revolutions in the second and 20^{23} revolutions in the last. Leonardo was aware that the enormous friction involved would result in a correspondingly enormous degree of heat. In fact, the whole point of the machine was to create the greatest speed and the highest temperature ever recorded: "The sun, which heats the whole world on which it shines and which, in twenty-four hours, travels such a lengthy path, would seem, in comparison to this instrument, stationary and cold". The heat of the third wheel would be so great that any inflammable object coming into contact with it would "immediately burst into flame"; and anyone touching the last wheel would "die instantly". Leonardo suggests various devices designed to limit the damage caused by such intense heat, including "diamond pintles", "tempered steel wheels" and water-fed cooling systems. If, however, what was required was an instrument producing "instant fire", the machine could be limited

Fig. 133. CA, f. 83 v/30 v-a.

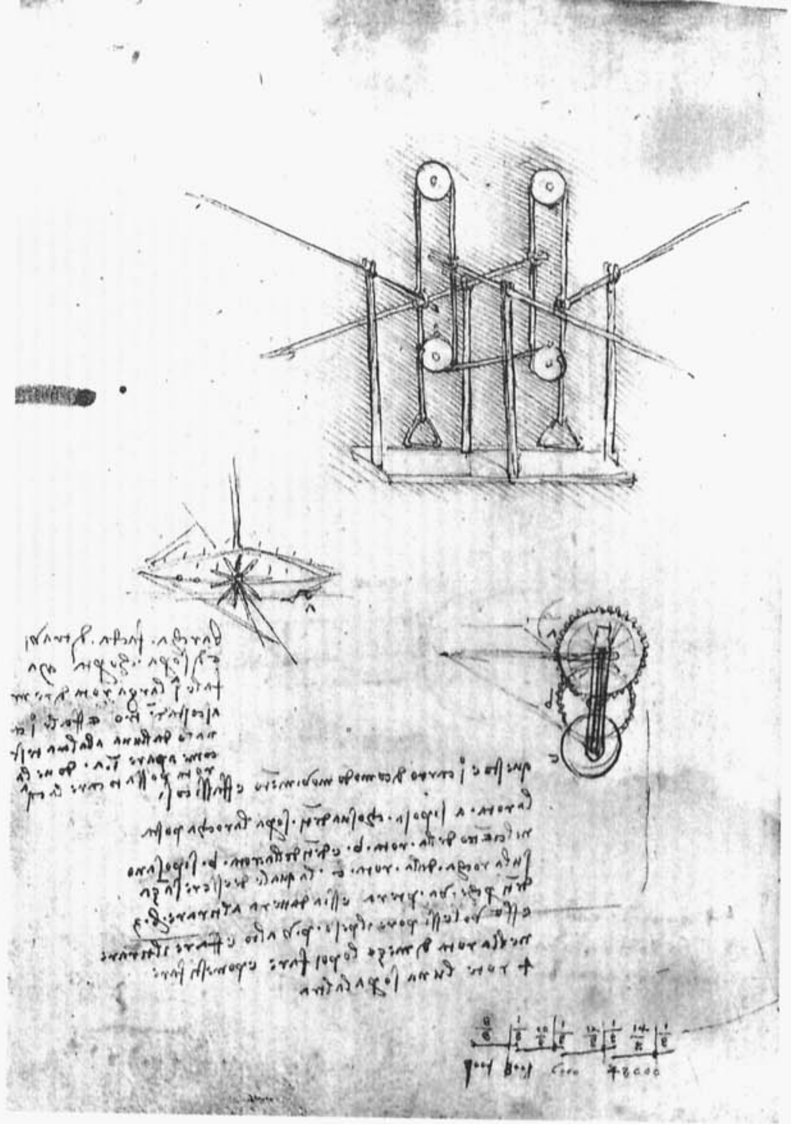

Fig. 134. Paris MS. B, f. 76 v.

to only six wheels. In his desire to know and state the number corresponding to 20^{23}, Leonardo invented an ingenious sytem of so-called "arithmetical proof". He wrote out, on twenty-four lines, the results of twenty-three multiplications and arrived at the following final number: "one hundred thousand million million million million million million million". Unfortunately, in completing this complicated operation he made a series of mistakes — a not unusual occurrence in his early writings — including losing, on the way, about six final zeros! This particular machine was never actually constructed, of course, but if it had been no one would have been able to counteract the enormous degree of friction.

A little further on in the same manuscript there is another sheet (f. 88 r/32 r-b) covered with drawings of pulley systems among which may be discerned two notes that make reference to another impossible dream: "A thirty-second part of a grain lifts two hundred pounds"[4] and "a silk thread raises up to 120 wheels with ten pounds of force; it raises six men weighing two hundred pounds each". The ancient hope of succeeding in developing limitless sources of energy clearly led Leonardo to forget the realities of friction — a subject that was nonetheless a notable preoccupation in his later writings.

Coupled with these dreams of tremendous power were the dizzyingly huge numbers — billions, trillions and quadrillions in contemporary language — that the limitations of Leonardo's vocabulary obliged him to express by repeating "a million million million...". On folio 57 r of Paris MS. I, dating from 1497, he designed certain complex mechanisms in which he reduced friction to a minimum by thinning down the pintles and establishing a ratio of 1:72 between the lever and the counter-lever; he came to the conclusion that one pound of force "will move in counter lever 26,873,280 pounds". (He raised seventy-two to the fourth power, but made an error in the three final figures). Another rule is stated on the verso of the same sheet: "One pound of force at *b* results in ten thousand thousand million pounds at *m*... and know that when the first one above makes one hundred thousand thousand million revolutions, the one below makes only one complete revolution". And he concludes triumphantly, "these are the marvels of mechanical invention".

About ten years earlier, Leonardo had drawn in Paris MS. B (ff. 76 v and 77 r: Figs 134 and 82) an "easily moving wagon" capable, so he maintained, of both lifting and transporting heavy weights. Two drawings appear on folio 77 r. On the right, we see a wagon on whose ordinary wheels is mounted a second series of cogged wheels, each of which rests on an eight-toothed pinion situated near the hub of the ground wheel. The weight — a huge bell — is not resting directly on the axles of the ground wheels, but on those of the wheels with sixty-four cogs; these are geared to the eight-toothed pinions so that each revolution of the ground wheels corresponds to an eighth of a revolution of the cogged wheels. The drawing on the left shows a wagon with another series of cogged wheels that are meshed to the ones below in the same increasing ratio so that each revolution of the ground wheels corresponds to one sixty-fourth of a revolution of the upper wheels. It is not clear how the bell is loaded onto the first wagon. In the second, however, the load consists of a mortar that is held by cables linked to a pulley attached to the top of a derrick frame which rests on the axles of the upper wheels. Giovanni Canestrini[5] has redrawn and constructed a version of this wagon in which he installs the derrick frame of the second drawing onto the cart of the first. In his interpretation, Canestrini assumes that the machine works by raising the weight as it moves forward: "Leonardo, installing on the two axles of the cart — which are linked to the lower wheels — two eight-toothed pinions or trundles that are meshed with two large wheels comprising sixty-four cogs placed above, on the uprights of the fulcrums, activates the drums of the winches, which are linked to these large cogged wheels, and makes use of the wheels themselves of the drawn cart" which thus fulfil a "crank function". (Leonardo's notes indicate that the diameter of the first cogged wheel exceeds that of the ground wheel by only five centimetres). The movement thus starts in the ground wheels and extends to the upper wheels at diminishing speed. On folio 76 v, which is the facing page, Leonardo sketched what can only be a detail of the second wagon (the one with the mortar on it), illustrating a close-up of one of the ground wheels on top of which two cogged wheels are placed, labelled from top to bottom with the letters *a*, *b* and *c*. The inscription reads: "Wheel *a* rests, with its cogs, on the pinion situated at the centre of wheel *b*; the cogs of wheel *b* rest on the pinion of wheel *c*, which should not be cogged, as it runs on the ground; and on the ground the traction is three *braccia*; and if you wanted to put on a heavier weight and have the traction done by the middle wheel, it would be possible — you could have four wheels one on top of the other". Canestrini does not believe that the third drawing represents a detail of the second, but interprets it as being "another device, similar in its basic design" which works in the opposite direction. The reason for this — unstated but clear — is that if the ground wheels are seen as "cranks", they would have to make eight revolutions for the second cogged wheels to make a sixty-fourth of a revolution; the wagon, meanwhile, would have to move forward at least thirty-seven metres (the circumference of the ground wheels being, according to Leonardo's indications, one and a half metres) before the "traction" was activated. Since this is impossible, Canestrini reverses the procedure and suggests that the upper wheel *a* should be "driven by a drop weight attached to a cable wound around its drum axle". As support for his view, he refers to a drawing of another wagon which was originally on a sheet in the same manuscript.[6] Canestrini fails to take into account, however, the fact that the similarity between the two drawings is quite superficial. This last wagon has only four ground wheels and carries a column which is raised at one end and resting on two converging trestles. The wagon is placed near the edge of a deep trench; a heavy weight descends by gravity from the stationary cart into the trench, pulling a rope linked to pulleys and thus raising one end of the column and moving it from a horizontal to a slanting position. The aim of the experiment, as the inscription indicates, is to discover how the weight "behaves depending on its slanting or horizontal position". The only point of the "traction", then, is to alter the position of the load on the stationary wagon; consequently, the cogged wheels of the preceding cart are unnecessary. The inversion of the action from top to bottom eliminates both the problem of moving the wagon before the weight is raised and of halting the upward movement of the load, which cannot last the whole time that the wagon is advancing. But this is not all: in the wagon on the left of folio 77 r, whatever the direction of the action, the three wheels, which are linked, work together and cause the wagon to move. The only logical interpretation is that the mortar is designed to be somehow raised and suspended from the upper pulley. Then, the downward force of the load would activate the "traction", which would be transmitted in an increasing ratio from one wheel to the next. Once the weight has completed its descent, the wagon should have moved forward somewhere between fifty and a hundred metres. What we have here is, in fact, a self-propelling vehicle designed for the transportation of heavy weights over short distances, with the weights themselves acting as the driving force. The traction, as Leonardo points out, can start with the second, third or fourth wheel depending, almost certainly, on the weight of the load and the distance to be covered. Whatever the case, the design remained an exclusively theoretical one and was never actually put into practice. Leonardo's accompanying words do nothing to clear up the mystery; they do, however, provide evidence of the inventor's excitement in contemplating the incredible amount of energy that would be produced: "This [wagon] is of tremendous power, and if you construct the wheels and the pinions according to the indications opposite, one hundred pounds of force will pull one million one hundred and forty-four thousand pounds!"

Rather than actual machines, many of Leonardo's drawings represent theoretical principles, intuitions or the germ of a mental process still a long way from its conclusion. We have already mentioned his sketch of a parachute that was never actually tested — or if it was, only at the cost of the tester's life. Another design worth noting is the drawing in Paris MS. B (f. 83 v: see Fig. 1) which is known today, somewhat sententiously, as the "helicopter". Leonardo wrote: "If this screw-like device is well made — that is, made of linen of which the pores are stopped up with starch — and it is turned swiftly, the said screw will make its female in the air and will rise high". He planned to experiment first of all with a "small paper model" and it is quite probable that, reduced to the size of a small toy, the contrivance would be able to turn at the required speed. The drawing, however, features a canvas spiral nearly ten metres in diameter; it is hard to imagine either how this could be "turned swiftly" or how it could be made sufficiently strong to bear the weight of the machine and its pilot.

Furthermore, if all the small holes in the canvas were stopped up, it would become impenetrable without actually being any stronger. It seems reasonable to conclude, then, that the drawing represents an important experiment expressing a scientific principle that was to find its application much later in the propeller or helicopter.

Many other sheets in Paris MS. B show mechanical flight devices intended for specific experiments, the aim of which was to calculate the force required to raise the machine, and to aid in the development of other systems of propulsion. Leonardo's confidence in the eventual practical result of these experiments seems to have been unbounded. He even went so far as to design a huge contraption (f. 89 r: see Fig. 83) fitted with a ladder (not unlike the retractable undercarriage of a modern airplane) and feet quite clearly designed for soft landings. And yet the central problem remained unsolved. Even larger is the airship illustrated on folio 80 r (Fig. 135). Despite the obvious disproportion between the weight of the machine and its inadequate means of propulsion, Leonardo believed he was close to success and proposed to test the device above a lake where, if problems arose, impact with the water would be unlikely to prove fatal. The persistence with which Leonardo continued to design machines and systems that were fundamentally impossible to realize is nonetheless impressive. It bears witness to an even greater faith than that with which Christopher Columbus faced the ocean. For the navigator did at least possess reasonably efficient and previously tested instruments; the risks he ran concerned the length of the voyage and possible exposure to unheard-of natural forces. The facing of these great enigmas required a level of physical courage analogous to Leonardo's intellectual daring. In 1505, sustained by his great conviction, Leonardo considered his triumphant success in this field to be imminent. He set about analyzing the flight of the great birds of prey and evaluating the possibility of launching his machine from the top of a mountain, whence — by moving the wings — he could keep it airborne for an extended period. These studies are actually the source of the traditional but false story that tells of an actual attempt at flight.

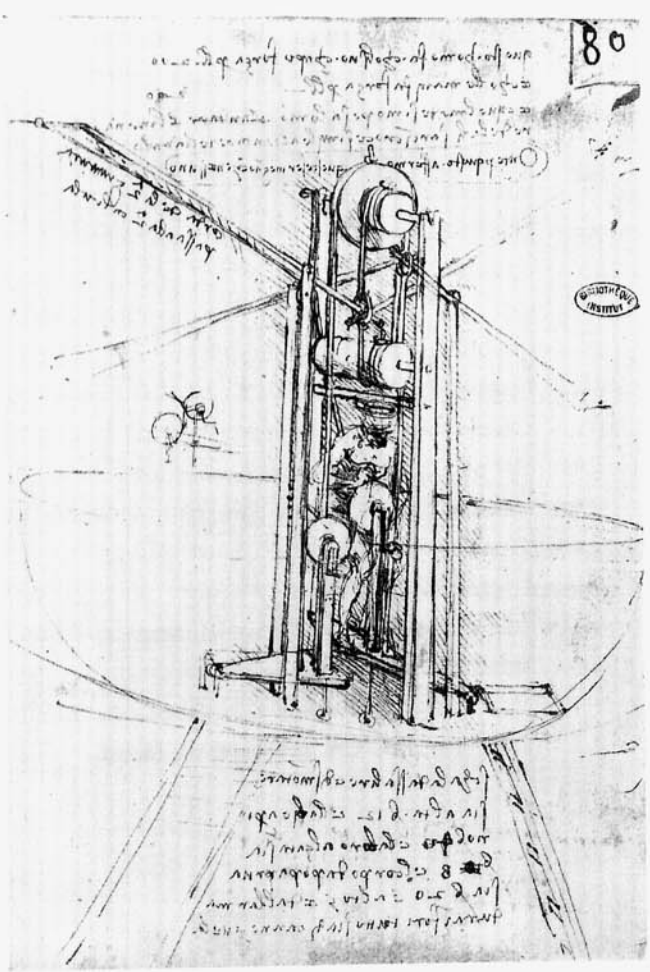

Fig. 135. Paris MS. B, f. 80 r.

The most sophisticated of all the wings designed by Leonardo was recently constructed and displayed in an exhibition of his machines organized by IBM. Even this device appeared to be too heavy. If, however, Leonardo had had today's ultra-light metals at his disposal, and if he had abandoned the moving wing and concentrated on the fixed wing, he would certainly have been able sooner or later to construct the first hang-glider, the conception of which was already almost complete in his mind.

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One of Leonardo's best-known machines is the famous self-propelling wagon (CA, f. 812 r/296 v-a: Fig. 136) that has been the focus of studies by various experts, including Semenza[7] and Canestrini.[8] Canestrini even constructed a model that is still exhibited regularly. The concept of a self-driven wagon was not an entirely new one: Francesco di Giorgio Martini's treatise includes vehicles "for hauling without beasts" which combine elements dating back even earlier. These teamless wagons were in the form of large, rectangular boxes containing the various mechanisms that caused the ground wheels to turn. The energy was provided by men positioned on the wagon, who turned the crank handles; these were linked to the ground wheels by a series of cogged wheels, pinions and an endless screw.[9] Leonardo's innovation resides in the introduction of springs that retain the energy with which they have been charged. Leonardo frequently introduced into his machines springs that had this capacity to release energy rapidly and to be as quickly recharged. It is not clear in this design, however, just how the essential operation of recharging is to be accomplished, given the enormous amount of energy necessary for continuous movement. It has been calculated that 370 springs would be required to cover a distance of only one kilometer on a flat surface. Despite the fact that they are reinforced, the two suspension springs visible in Leonardo's drawing would provide only a brief initial push.

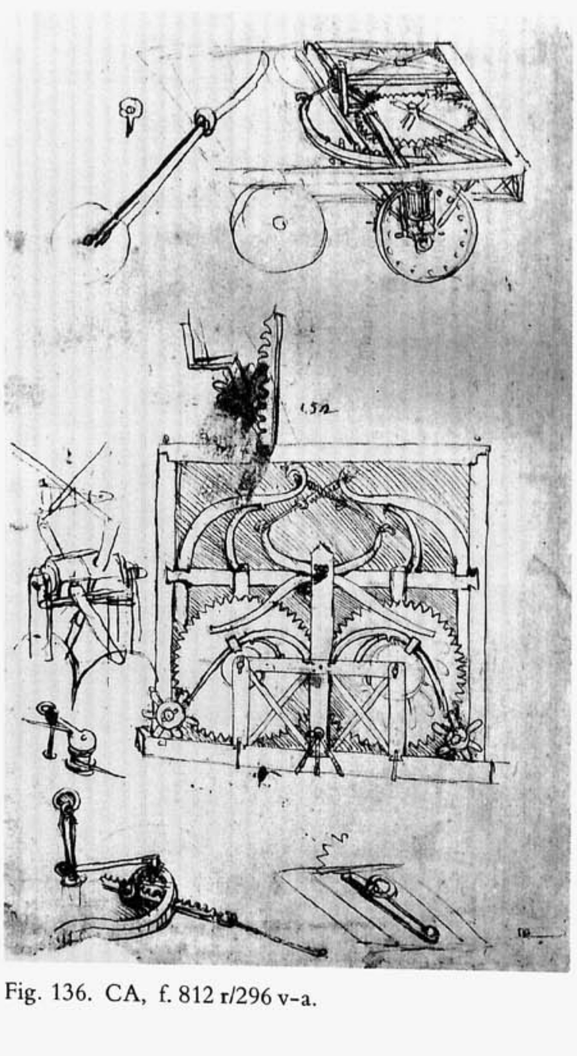

Fig. 136. CA, f. 812 r/296 v-a.

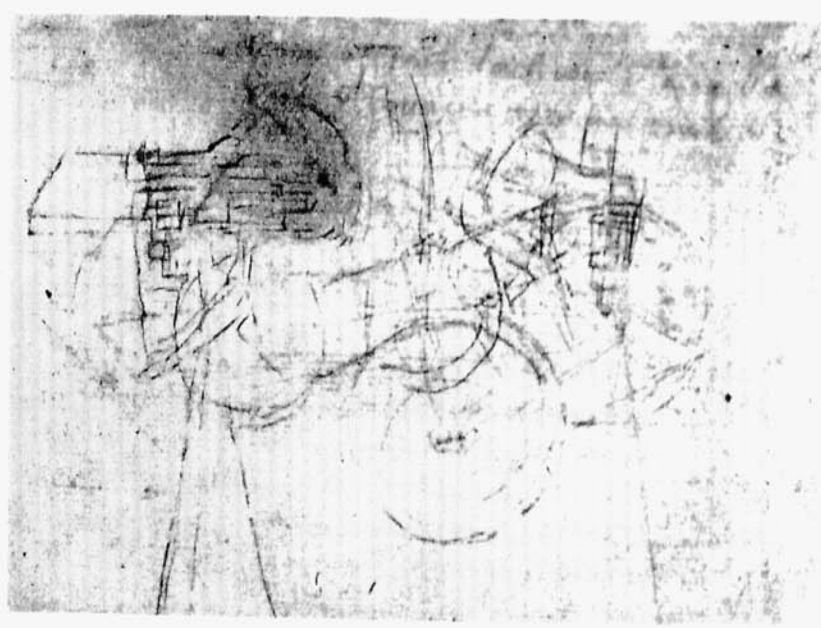

Fig. 137. CA, f. 114 r/40 r-b (detail).

The interpretation of folio 812 r/296 v-a of the Codex Atlanticus is indeed problematic and controversial. A first drawing at the top of the page shows a perspective view of the wagon, but the picture given is incomplete: a preliminary lead-point sketch has been gone over in ink and only the rear section is drawn in full detail. This completed section includes the driving mechanism and part of the transmission, consisting of a trundle gear which conveys movement to the wheel by acting on a ring of pegs located inside it. The front part of the vehicle is practically non-existent: from the few strokes that have been drawn over in ink we can decipher a sort of steering shaft attached to the front edge of the wagon and, sketched in the lightest and briefest of strokes, the front left-hand wheel. On the other side, we can just make out at least two other wheels drawn in lead-point — these are not visible in photographs — which are clear evidence of Leonardo's indecision regarding the steering system of the wagon. The design was obviously abandoned before completion. The shaft, as it appears in the drawing, is certainly no guarantee of the effective manoeuvrability of the wagon.

On the bottom part of the page can be seen a carefully executed ink sketch of the driving mechanism (this time seen from above) that features various modifications to the upper drawing: a counter-spring has been added to each of the suspension springs and one series of pegs has been removed. A tenaille has also been added, along with straps equipped with counter-springs that end between the six teeth of the two small pinions. Even the structure of the chassis itself (the cross and side members) has been altered. Certain imperfections apparent in the drawing — the fact that, for example, as the chassis base is shorter on the left than the right it is not absolutely rectilinear — are not important; what is significant is the distance between the two horizontal cogged wheels. According to Semenza, "they are meshed so as to turn in opposite directions and are thus the equivalent of the part known in the modern automobile as the differential". It is our view, however, that these wheels are too far apart to be geared together; in any case, their centres are rigidly fixed, which excludes the possibility of one wheel turning around the other while the latter remains stationary. The six mechanical devices sketched around the chassis pose another serious problem. It is impossible to interpret them as tools; they are more likely mechanisms forming part of the machine itself.

Two conclusions can be drawn regarding this sheet of the Codex Atlanticus. The first concerns the incomplete nature of the upper drawing: this indicates that the steering mechanism of the vehicle was as yet undefined. The second focuses on the six mechanisms, the integration of which into the machine would alter it radically. If we are correct — and it seems that we might be — in attributing a special function to each of the mechanisms, we are obliged to conclude that they represent a later phase in the development of Leonardo's design and that both drawings of the wagon can be considered to have been superceded by them.

The reconstruction of the self-propelling wagon executed by the engineer Canestrini is not an absolutely accurate rendition of Leonardo's drawing. The springs are very near the front edge of the wagon, and the doubtful area of the original sketch that was not gone over in ink has been resolved somewhat arbitrarily, the wheel placed by Leonardo under the left-hand edge having been moved to the centre. We are far from convinced, however, that Leonardo's aim was to construct a tricycle. Furthermore, the central wheel in Canestrini's reconstruction turns freely on its axis. The addition of a tiller handle would transform it into an excellent steering system, rendering the awkward, cumbersome steering-shaft quite superflous. The wagon cannot move, of course, for neither the problem of the transmission of motion nor that of energy production has been solved.

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Until recently, Leonardo scholars generally used the Hœpli edition of the Codex Atlanticus, which was published between 1894 and 1904. At that time, photographic plates were not very sensitive and as a result only a small part of another drawing of a vehicle (f. 114 r/40 r-b: Fig. 137) was visible in that facsimile edition.[10]. Leonardo made his drawing in pencil — or rather in the ancestor of the modern pencil, which consisted of a stick of lead and tin whose traces on the paper were too faint to leave an impression on early photographic plates. Only a small head was visible and this almost certainly because a greasy mark — probably a fingerprint — had caused more of the metallic powder to adhere in this area than on the rest of the drawing. Even on the original, deciphering is complicated by the transparency of the paper and the presence of an ink drawing on the verso, the bolder lines of which interfere with the more delicate sketch on the recto. A recent photograph, executed using special techniques, has made the drawing clearer and eliminated the disturbing effects of transparency. It is now possible to see that the small head belongs to a man who is seated on a box with wheels and a backrest. The man's legs are crossed and his feet are apparently resting on a small rectangular platform; above this is an unusual vertical chassis that partially conceals a semicircular shape that might possibly be a wheel. We believe that the chassis is actually double and that the circular shape — the wheel — is situated between its two halves. The man's arms are open and slightly bent; his right hand appears to be operating some kind of mechanism, while the left is just barely sketched in. Many of the original lines have virtually disappeared, but it seems evident that the drawing represents a vehicle being driven by a seated man. Indeed, the rear part of the sketch comprises various highly detailed elements — the ring of pegs on the right-hand rear wheel that is connected to a trundle gear, for example — that link the vehicle closely to the one depicted on folio 812 r/296 v-a of the Codex Atlanticus. The gear system itself possesses an interesting new feature not present in the wagon on folio 812 r: its diameter is reduced twice between the top and the base, indicating a three-speed mechanism. This requires a system that moves the gears both horizontally and vertically, so as not to lose contact with the wheel pegs. This mechanism is probably represented by the half-visible rectangle that juts out above the trundle. Given that the drawing is a rough preliminary sketch — somewhat rudimentary and full of omissions — of a general view of a self-propelling wagon, its interpretation is, in various ways, difficult and ambiguous. The one that we suggest, although carefully considered, does not profess to be entirely beyond doubt.

The driving force for the trundle-wheel-wagon arrangement is provided by two large suspension systems with semicircular springs (one concave and one convex) the exact nature of which — due to the fragmentary character and roughness of the drawing — is not immediately clear. They cover the whole width of the wagon. Various well-defined features, such as the motor device and the transmission mechanism, are grouped within a triangular chassis. Even if each vague, confused line, of the drawing were submitted to a detailed analysis, the answers would not necessarily be obvious. Nevertheless, it does at least seem clear that the hub of each of the two wheels is joined to converging, rather than parallel rods. The point, or rather the line, of convergence of the rods and of junction with the front section of the wagon appears to be indicated by a double vertical line that can be seen on the box on which the driver is seated. What we seem to have here, then, is a new model of self-propelling wagon with two articulated sections, one providing the power and the other bearing the steering mechanism. The problem of steering, with which Leonardo failed to come to terms on folio 812 r/

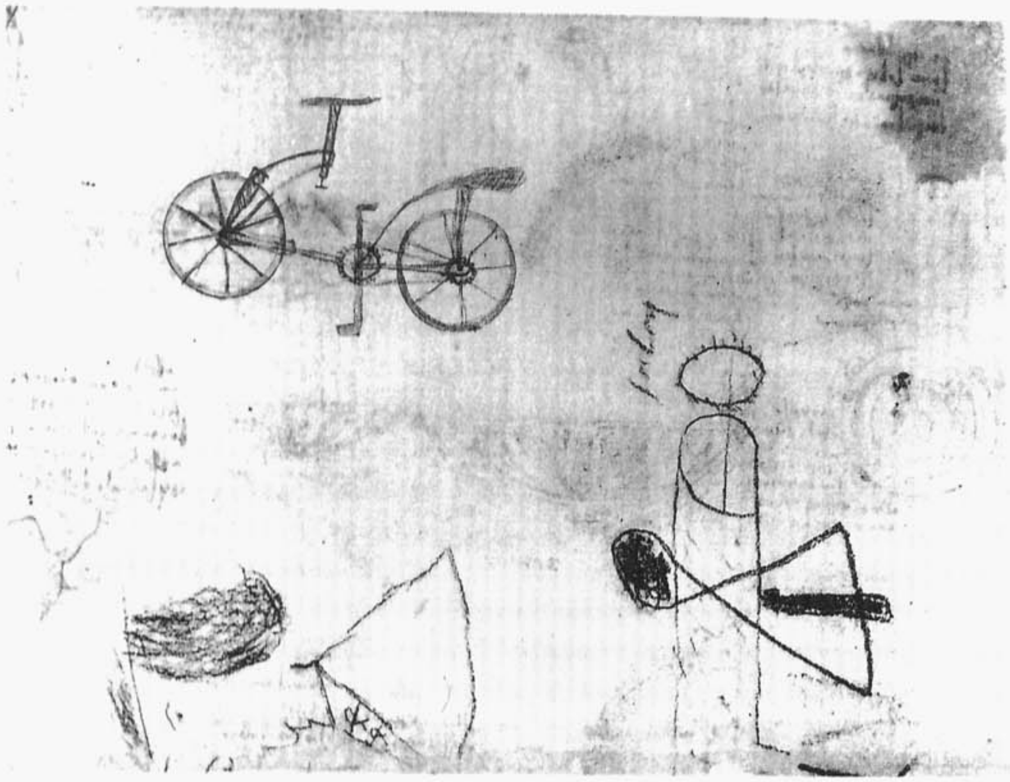

Fig. 138. CA, f. 133 v.

296 v–a, seems to have been resolved here. As the wagon is articulated the steering section receives the thrust in only one direction, around which there is a broad angle of rotation both to the right and the left. Difficulties in the interpretation of this drawing are due not only to the faintness and incompleteness of the strokes, but also to the presence of lines which Leonardo, in making corrections, partially erased or redrew (in the area of the man's left arm, for example). Some scholars have expressed doubts concerning the position of the driver and the whole steering section. Is the man seated facing in the same direction as the movement of the wagon, or sideways? In the former case, two rear wheels must be situated behind the driver (hidden by the backrest), making a total of six wheels in all. The two front wheels would then be represented by the one in the foreground and the one on the extreme left; but if we look closely, we see that these are neither parallel nor of the same diameter. Furthermore, if the front section was indeed positioned in this way, it would receive the thrust of the motor section from the side rather than from the rear, which is patently absurd. The wagon must, therefore, have five wheels: two on the motor section, and three on the steering section. The first — which Leonardo has made transparent so as to render the man's legs visible — is quite clear; the second is partially concealed by the vertical double chassis and the third is hidden by the second. The driver is seated sideways (as is still the case in many agricultural machines). His right arm controls the steering and, if the drawing were more complete, his left hand might possibly be recharging the springs. Although the design is in its early stages and its presentation is cursory, all the essential elements are there: the ring of pegs on the wheel, the three-speed trundle gear system, the two-spring suspension propulsion system and the two articulated sections which improve steering efficiency. The weak point is still the motor, which could never provide the necessary power. But the force of Leonardo's extraordinarily creative, indefatigable personality is as evident as ever.

This drawing dates from a period several years later than the sketch on folio 812 r/296 v–a, but both were apparently executed before Leonardo left Florence and settled in Milan.

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Another even more astonishing drawing has recently come to light. It appears on the verso of folio 133 v (previously f. 48) of the Codex Atlanticus (Fig. 138), which was originally part of the same sheet as folio 132 r/48 r-a. This sheet was one of the many that Leonardo passed on to his pupils who, to practise their drawing skills, would copy the master's sketches and devise new ones, frequently adding — for amusement — various caricatures and obscenities. This must have been the fate of this particular sheet. But the pupils' additions remained undiscovered in this case until the 1960s. The sheet, although scribbled all over on one side, was not thrown away. Leonardo, who was extremely economical in his consumption of paper, used it (along with other similar ones that have also been discovered) on the back, which was still blank. Having folded the sheet in half, and keeping the fold toward the top, he covered the two half-pages with notes and drawings in such a way that when the sheet was unfolded the two halves were upside down in relation to one another. Towards the end of the sixteenth century, almost the entire treasure of Leonardo's manuscripts came into the hands of Pompeo Leoni. To prevent the scattering of so many loose papers, Leoni assembled them in two albums, one of which — due to its format — was called the Codex Atlanticus ("atlas-sized collection"). When a sheet bore Leonardo's writings and drawings on both sides, Leoni would insert it into an empty "window" cut out of one of the pages of the album, thus rendering both faces visible. The same visibility was, however, denied the pages that had been sketched and scribbled on by Leonardo's pupils. If the sheets that had been folded in two were opened up to be glued, they appeared too big. Leoni thus cut them near the fold, trimmed the edges of the two halves and turned one of them around so that the writing all went in the same direction. He then inserted the two pieces into the album, inevitably concealing the students' work. This would have been their ultimate fate had the Codex Atlanticus not undergone restoration during the period between 1960 and 1970. Once they had been detached from the old album, the original unity of folios 132 and 133 became obvious and a detailed examination of their content was made possible. The most interesting — and unskilful — of all the drawings depicts a two-wheeled vehicle that we are tempted to call a bicycle, although it is a contraption very different from any bicycle that ever existed. The person who drew it was almost certainly a young, inexperienced boy. The compass he used to draw the wheels (which are ordinary cartwheels) was obviously a little slack, and the spokes are sketched in a shaky, unsteady fashion. The frame consists of a single rod, at the centre of which is installed a cogged wheel attached to two exaggeratedly long pedals. The cogs are in wood and are cube-shaped to avoid breakage during the strain of traction; they are designed to mesh with the large openings of a chain that links them to a

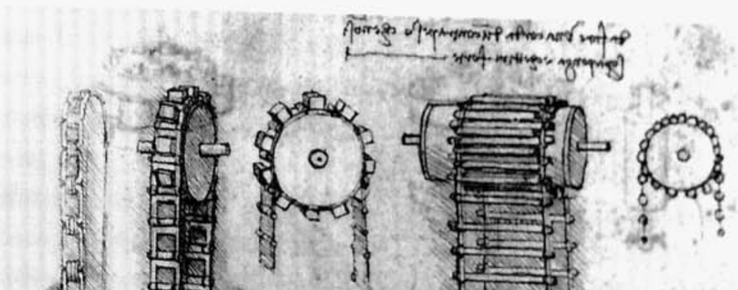

Fig. 139. Madrid MS. I, f. 10 r (detail).

second, smaller cogged wheel situated at the hub of the rear wheel and that thus transmits the movement from the large wheel to the smaller one. The rather strange saddle is attached to both sides of the hub of the rear wheel and to the centre of the frame to prevent buckling. Attached to the hub of the front wheel are two curved rods that support a pair of primitive handlebars; the rods are positioned so as to minimize friction with the wheel. There does not appear to be any steering device. This deficiency, combined with the cubic shape of the cogs, means that the vehicle could never function like a real bicycle. But these details are important, for Madrid MS. I, (f. 10 r: Fig. 139) contains a drawing by Leonardo that illustrates an identical chain and a wheel with cubic cogs. The fact that the machine could never work is nothing unusual — it is even a guarantee of its authenticity. In fact, these were not actual machines, but simply ideas: this sketch represents the first conception of a bicycle that ever took root in a man's imagination. And that man could only have been Leonardo.

Once he had designed this type of cogged wheel with a transmission chain, Leonardo must have had the idea of applying it to a two-wheeled vehicle, the propulsive force of which could be provided by a pair of human legs. The machine was certainly neither built nor tested; if it had been, Leonardo would soon have discovered the need for a steering system and pointed cogs.

Leonardo's original drawing of this "bicycle" must have been lost, but — according to our highly probable reconstruction of the facts — not before an inexpert copy was made by a student. The nickname of this young person is the only word that appears on the sheet; his real name was Giacomo Caprotti, and he entered Leonardo's studio in 1490 as a servant and model. On what was originally the first page of Paris MS. C (now f. 15 v), Leonardo himself notes the young man's misdeeds, and describes him as "a thief, a liar, obstinate and greedy". Among other things, he apparently stole money from his comrades Marco d'Oggiono and Gian Antonio Boltraffio. The nickname given to this rascal was taken from Luigi Pulci's mock-epic poem *Morgante Maggiore*: "*Salaì*", meaning "devil". It was almost certainly one of the young scamp's victims who, anxious for revenge, drew his caricature — which includes a ridiculously long nose shaped like a chicken's beak — next to the sketch of the bicycle. The same caricaturist, or one of his fellows, also added an image of a phallus pointing towards an anus, above which appears the word "*salay*".

Certain scholars, although ready, as a rule, to laud the innovative brilliance of Leonardo the "universal genius", nonetheless find it difficult to accept that he actually invented a bicycle. As a result, they suggest that the drawing in question may be a recent forgery. It is not enough, however, simply to put forward a hypothesis: it must be supported by plausible arguments.

Since the invention of the bicycle chain dates from the second half of the nineteenth century, at which time the Codex Atlanticus was safely ensconced in the Ambrosiana Library, we have to imagine — if we want to reconstruct the forgery theory — that a young man (or some other individual without drawing experience) gained entrance to the library, perhaps in the early years of our own century, and requested permission to consult the Codex — permission not readily granted. Having nonetheless obtained it, the presumed forger would have had to remove a glued sheet (a long, delicate operation) and then, using a compass, a pencil and a brown pastel to render the wooden portions, draw a bicycle quite different from any he had ever seen, inventing peculiar handlebars with no steering device and — a brilliant final touch — adding a wheel with cubic cogs and a strange chain the like of which was to be found only in an as yet undiscovered manuscript in Madrid. After all this, he would have had to glue the sheet back into the Codex, under the indifferent gaze of the librarians. A perfect crime and one utterly without motive — unless, of course, its author somehow foresaw that the Codex Atlanticus would one day be restored and that the bicycle, once it had come to light, would sow confusion among scholars. This hypothesis takes no account, furthermore, of the connections between the bicycle and the other drawings that surround it. It is up to the reader to choose the most plausible explanation.

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Not all of Leonardo's machines are as daring or as unworkable as the ones we have discussed. In any event, it would be impossible to examine them all here. Our selection is designed to emphasize the most important features of Leonardo's activity as an engineer, not while under the orders of any particular patron, but when he was working and inventing freely, his own master, pursuing all the visions his imagination could conjure up and not halting even when faced with the impossible. Leonardo's technogical "whims" seemed, to his contemporaries, both odd and dangerous, for they distracted him from art. But art, science and technological invention were all closely linked in Leonardo's philosophy. His approach — which was based on a belief in the absolute inertia and passivity of matter — necessarily included an acceptance of those philosophers who perceived behind the movement that animates nature and creates life, the action of immaterial forces such as light, heat, energy and gravity. Beauty itself could not be the result solely of the balanced proportions of bodies, but had its source also in the emanation from their surfaces of incredibly dynamic intangible forces. Leonardo, who accepted Ficino's definition of beauty as *actus vivacitas*, was constantly reminding painters that they should imbue their figures with the "vivacity of action", the very throb of life. In creating movement and life, these forces are controlled by Necessity; they are subject to the laws of mathematics and are dependant on material structures established *ab aeterno*. It is for this reason that Leonardo believed that the painter must become a scientist whose aim is to discover underlying principles and structures (of anatomy and of the mechanics of motion in liquids and solids). Once these laws are revealed to him, his imagination — now virtually divine — must invent new devices which even Nature does not create. But the full extent of Nature's power, which allows her to breathe life into her animal and plant creations, is denied him. Man's machines must always receive their power from an outside source. They thus have no life of their own, but represent only its shadowy likeness.