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LEONARDO'S THEORY OF DYNAMICS

By Professor Pascal Brioiist (Centre for Higher Renaissance Studies, Tours University)¹. The motion of bodies is discussed in several Leonardian manuscripts and the diversity of these statements demonstrates how Leonardo's conceptions evolved over time. The Arundel and the Leicester Manuscripts reveal his interests in this fascinating field of research.

Although Leonardo confessed to "not being a man of letters", with a touch of sarcasm against his contemporaries, he firmly countered those who claimed he was "a man without learning".² It is true that as an illegitimate son he had no access to university and was not taught ancient languages, but after his formative years in Verrochio's workshop, he started to teach himself Latin, an enterprise evidenced by long lists of vocabulary and conjugation dating from the 1490's.³ Furthermore, he maintained close relations within the university milieu all through his life. For instance, he knew Giovanni Marliani, the author of a *De proportione motuum in velocitate* who loaned him a treatise on algebra. He was also in very friendly terms with the physician Fazio Cardano who taught in Pavia and through him, he had access to Albert of Saxony's *De proportione motuum* and to Alexander Achilini's *De proportionibus motuum*. He also obtained, through another Milanese physician, Stefano Capponi, the opportunity to consult a book wrongly attributed to Euclid entitled *De ponderibus*. This text discussed ideas about the fall of heavy things and about the proportionality of the speed of falling bodies according to their weight.⁴ The French philosopher Pierre Duhem was the first scholar to explain that Leonardo had acquired a certain knowledge of the medieval commentators of Aristotle, the so called *calculatores*, through his friends in Milan.⁵ Despite the argument of Giorgio de Santillana, who claimed that Leonardo would not have been able to read such complicated philosophical texts, the current consensus, noting that Leonardo precisely quotes from authors like Albert of Saxony, has dispensed with this prejudice, and accepts the central core of Duhem's thesis.⁶

At about the same period that he was learning Latin, Leonardo also developed an interest in ballistics. He sometimes worked at the arsenal and studied the bombards and the newly cast cannons of the Sforza alongside expert founders like master Zanin and master Albergeto.⁷ He conducted research into the maximum efficiency of artillery pieces, examining the trajectories of the shots and trying to make sense of the relation between a certain quantity of black powder, the elevation and the range of the piece.⁸ Most of the time, he used the rule of thumb familiar to artillery men of the period, but since at the same time he was studying the Aristotelian mechanics, a new field of investigation was opened to him.⁹

¹ The author would like to gratefully acknowledge the assistance of Pierre Iselin, Carla Mitchell and Michael Berlin.

² C.A. 119v/327v.

³ See Codex Trivulziano fol 8r and 9v and fol 50r 51v, or CA 213 verso-b, and fol. 1025. Augusto Marinoni, *Gli appunti grammaticali e lessicali di Leonardo da Vinci. I.L'educazione letteraria di Leonardo*, Milano, 1944.

⁴ Ces travaux sont cités dans le Ms I fol. 102r et 130 r et dans le Ms M.

⁵ Pierre Duhem, *Léonard de Vinci, ceux qu'il a lus, ceux qui l'ont lu, 1906-1913*, Edition des Archives Contemporaines, Paris, 1984, and, *Etudes sur Léonard de Vinci*, vol. I and II, 1906-1909. Amongst the medieval authors quoted by Leonardo are Richard Swineshead, Thomas Heytsbury (the *calculatores* of the Merton School), Albert of Saxony, Bagio Pelacani and Angelo da Fossombrone.

⁶ Giorgio de Santillana, « Léonard et ceux qu'il n'a pas lus », p.43-57, dans *Léonard de Vinci et l'expérience scientifique au XVIe siècle*, Koyré Alexandre (dir.), Paris, 1953 and Carlo Vecce, *La biblioteca perduta : i libri di Leonardo*, Roma, Salerno editrice, 2017

⁷ Pascal Brioiist, *Léonard, homme de guerre*, Alma, Paris, 2013, p.111.

⁸ See for instance Ms I of the Institut de France, fols. 84r, 128v and 130r.

⁹ Pascal Brioiist, « Bombards and noisy bullets » in *Illuminating Leonardo. A Festschrift for Carlo Pedretti celebrating his 70 years of scholarship (1944-2014)*, ed. by Constance Moffat et Sara Tagliagamla, Brill,

Leonardo's awareness of Aristotelian visions of physics is quite obvious in the *Codex Arundel*. Some excerpts of this manuscript refer directly to Aristotle's chapter on motion¹⁰:

*Every heavy body desires that its centre would be the centre of all the elements. And the one that is free falls in the direction of this centre [...] Gravity is the force, daughter of the motion, and sister of the impulsion and of percussion [...] Every heavy body desires to lose its gravity*¹¹.

A number of Aristotelian ideas can be identified here. Firstly, this alludes to the heavy elements in nature (namely earth and water and any element composed of the two previous basics), and to the fact that they are seeking their natural place, the centre of a sphere. The motive force of these elements is the "desire" to leave their current place to occupy a new place where gravity will be cancelled. Leonardo describes exactly what is natural motion in his characteristically anthropomorphic way. Macrocosm and microcosm are echoing each other.

Elsewhere, Leonardo also tries to evaluate the acceleration of a falling body within a medium of uniform quality and proposes a proportional law of his own that bears the imprint of his wider reading:

*The weight which descends freely acquires a degree of movement with every degree of time, and with every degree of movement it acquires a degree of velocity. Although the equal division of the movement of time cannot be stated by degrees as is the movement made by bodies, nevertheless I must in this case make the degrees after the manner in which they are made among musicians. Let us say that in the first degree of time the weight acquires a degree of movement and a degree of velocity, then it will acquire two degrees of movement and two of velocity in the second degree of time and so it continues in succession*¹². . .

From Albert of Saxony, Leonardo borrowed the concept that velocity increases proportionally to the time of the fall from the moment of the beginning of the fall. Leonardo calls that a pyramidal power.

On another folio, Leonardo discusses the so called violent motion, that is the kind of motion that opposes itself to natural motion because of an external mover providing a force:

*Gravity, force and percussion are of such nature that any of those three by itself can be born of the others and give birth to one of the others. Gravity and force can be called sisters and of an equal nature because they are generated by the same cause and live according to the same desire and they die in the same way. [...] Weight, when it moves according to its desire, always increases but in the same situation, the force decreases. Weight desires only one line while the force desires an infinity of them. The weight has the same power all through its life while force goes always weakening*¹³.

Boston, 2016. On Leonardo's ideas about proportionality in Ms I and Ms M, see Paolo Galluzzi, "Leonardo e I proporzionanti", *XXVIII Lettura Vinciana*, Giunti Barbera, Florence, 1988.

¹⁰ *Aristotle's Physics*. Translated by Waterfield, Robin. Bostock, David (Introduction and Notes), ed., Oxford University Press, 1999.

¹¹ *Codex Arundel*, folio 184v. My translation

¹² *Manuscrit de l'Institut de France Codex M fol.45r*. Translation Theresa Wells, *from Leonardo da Vinci Notebooks*, Oxford University Press, 2008.

¹³ *Codex Arundel*, Folio 37v. My translation.

Leonardo points out that when an element comes closer to its natural place, it accelerates to reach it more quickly following the same straight line. Alternatively, when an object is thrown by a force, in any direction, its violent motion goes on decreasing. A force is also required to keep an object moving, be it natural or violent. In other excerpts, Leonardo considers through diverse “thought experiments” how heavy objects could be slowed down during movement through the air. Through his complicated language he fine tunes and adjusts his ideas.

But if the power of the mover would be in proportion with what is moved, then the motion of the object would be in the first degree of its value. As if I wanted to drag a balloon full of air against the wind, the which would be moved by excessive power, the wind, where it pushes it, would exert, because of its concentration, such resistance that the balloon that is rammed inside, would leap backwards, not unlike if it bumped against a wall. But if this balloon would be moved by a mover which has power and motion proportionate to the lightness of the aforementioned medium, then that motion will go on as much as its power will slowly push the air which is opposed to its path¹⁴.

In other words, if you move an object through the air with great force, air will oppose strong resistance because it concentrates on the front of the moving object but if you move it with a lesser force, the resistance will be weaker. Leonardo is very interested in the role played by the medium, in this case air, in acceleration or deceleration.

Leonardo raised here an important question: when an object has begun its movement, launched by a mover (e.g. the hand of a man throwing a stone, a bow firing an arrow, a bombard throwing a bullet), why does this object continue its trajectory? How does it keep its momentum? His answer was that the air effectuates the transmission of the motion. Waves form in front of the movable thing itself because this thing collides with the air and eliminates the frontal resistance. The air waves rush behind to fill the void created by the displacement of the object and the whirlpools of air, closing in behind, push the object forward.

The air that runs behind the movable thing, which runs because of it, is set in motion by the impulsion applied to the movable thing, and that air, expanded by the great wave, ramming the other air, goes back behind and with great circulation, diminishing in its extremities, finally stops and does not follow the object¹⁵.

This theory, which presupposes that the air waves are quicker than the object that produced them, described by Leonardo in Ms F, was called by Aristotle’s Latin translators *antiperistasis*. Around 1492, Leonardo used this hypothesis to elaborate a related theory about the location of the maximum velocity of a bullet in its trajectory. Having considered that the course of the shot is defined by a combination of violent motion and natural motion he argued that the maximum power of force against the resisting medium must be in the middle of the straight line of the trajectory, when the original impulsion of the powder is not yet consumed¹⁶. We know today that his conclusion is wrong. Leonardo later came to doubt that the velocity of the air waves could be faster than the movable object’s velocity¹⁷. This lead him to ask the question : What is impetus?

¹⁴ Codex Arundel folio 54r. My Translation

¹⁵ Manuscrit de l’Institut de France, codex F, folio 74 r. Translation Theresa Wells.

¹⁶ Manuscrit de l’Institut de France, Codex A folio 43v. Translation Theresa Wells.

¹⁷ Codex Atlanticus folio 542 r My Translation

*Impetus is a power created by movement and transmitted from the mover to the movable thing; and this movable thing has as much movement as the impetus has life.*¹⁸

Here he finds inspiration in a hypothesis developed by medieval philosophers: the impetus is not fed by whirlpools but is rather a quality introduced by the mover into the object. This quality can either decrease or increase according to certain proportions and mathematical rules. This is what mathematicians like Thomas Heytesbury and Richard Swineshead had studied. Leonardo had probably heard about them because their ideas were discussed in Italy in his time by scholars such as Angelo da Fossombrone, Gaetano da Thiene and Bernardo Torni¹⁹. Around 1504, Leonardo proposed an experiment to prove his point.

*It is proved how the air does not push the movable thing since it is separated by the power of its mover. If to the movable thing which separates itself from its mover there was given the perception of the movement of the air which pushed it behind, it would happen that the bullet of the arquebus in penetrating a leathern bottle full of water would immediately lose its movement at the beginning of its penetration, because instantly the water would close the entrance and separate it from the air which drives it; as to which experience shows to the contrary, seeing that this ball after the said penetration of the water moves for a long time. And if you were to say that the fury of the movement of the air or of the water, through which this bullet passes, which turns to fill up the vacuum from which the bullet departs point by point, is that which forms a wedge between the back of the bullet and the rest of the air which stays behind it; here the reply is that the air is more powerful and more compressed in front of the bullet than that on the opposite side, because this opposite side is the air reflected by the percussion of the bullet*²⁰.

It is difficult to be sure if Leonardo was proposing here a real experiment or only a theoretical one but the argument is strong: if the bullet enters the leather flask, there is no air inside so, according to the *antiperistasis* theory, there should be no air waves to propel the bullet. Hence, if the bullet goes through the flask, Aristotle is proved wrong. Leonardo goes on destroying his previous certitudes with another proposal:

*'The reflection of anything is always of less power than its incidence'; and if you should again say me as to this by urging that this power cannot be infused in the body that is moved, because 'no movable thing moves of itself, unless its members exert force in other bodies outside it', as when a man in the center of a boat pulls the rope attached to the stern of it, in order to give movement to the ship, which work is useless unless this rope is fastened to the bank where he wishes to move, or unless he pushes the oars in the water or the pole on the bottom; therefore the power not being in the air which drives the said bullet it is necessary that it is poured into the bullet; and if it is thus poured what has been said above serves as an example of the result; and in addition to this, this power so poured in would be of equal force through all its sides, because it would be spread equally in equal quantities through all that bullet; this however is not so, and the other premise you do not grant me*²¹.

¹⁸ Manuscrit de l'Institut de France, Codex E 22r. (Translation E. Theresa Wells).

¹⁹ Pascal Briost, «Leonardo da Vinci e la scienza della dinamica del suo tempo», *Scienze e Rappresentazioni. Saggi in onore di Pierre Souffrin*, ed. by Pierre Caye and alii, Olschki Florence, 2016.

²⁰ Codex Leicester, folio 29^v. (translation Theresa Wells but I preferred to translate scoppieto by arquebus).

²¹ Codex Leicester fol.29^v. (translation Theresa Wells)

Another issue for Leonardo was to model what exactly happens in the air when a body passes through it. Some lines after the previous excerpt, he proceeded to consider the similarity between the aquatic and the atmospheric mediums and used an analogy to invent a new experimental protocol:

If you wish to see the movement the air makes when it is penetrated by a movable thing take an example in the water, that is, underneath its surface, for it may have mingling with it thin millet or other minute seed which floats at every stage of height of the water; and afterwards place some movable thing within it which floats in the water and you will see the revolution of the water, which ought to be in a square glass vessel shaped like a box. 'Every natural act is communicated from the doer to the object in the shortest possible time'; and the air beaten and compressed by the movable thing that moves within it need not therefore be that which restores the vacuum, for the movable thing makes a succession of vacuums as it flies from it; but it is that which is nearer the opposite side of the movable thing, that is that by which it leaves the path, that continually rarefies the condensation already made; and by means of this rarefaction the before mentioned vacuum is restored. 'Never, in the same time will the greater power be subdued by the lesser power'²².

This is not the only time Leonardo made use of the idea of grains of millet to visualize a vortex in water, he also used the same conceit when he studied the behavior of blood in cardiac valves²³. It is nevertheless remarkable that he drew on such a powerful arsenal of rhetoric, combining syllogisms and experiments (real or fictional) to dismiss the Aristotelian tradition.

Leonardo's studies of dynamics, although inspired by practical questions regarding ballistics, did not transform gunnery techniques. Niccolo Tartaglia, proposed in 1537 a geometrical approach to ballistics derived from Aristotle and Archimedes, and his two works, the *Nuova Scientia* (1537) and his *Quesiti* (1546) were eventually taught within the Spanish artillery academies. However, he did not question the central concepts of *antiperistasis* and *impetus*. It was only in the 1600's that Thomas Harriot and Galileo Galilei tried simultaneously to deduce from the medieval theories of impetus some rules concerning the range of a gun in relation to its elevation. In this way, Leonardo was ahead of his time. Yet in around 1504, when he drew parabolic ballistic curves in the Madrid Codex, he was convinced that the best range would be achieved with an angle elevation of 10° (Tartaglia definitively demonstrated later it was 45°). Leonardo was also wrong in evaluating the other ranges according to the different elevations²⁴. Thus, this most precocious of theoreticians was able to question Aristotelian received wisdom but the practical implications of his speculations were useless for gunners.

Six illustrations:

Codex Leicester folio 29v.

Codex F (Manuscrits de l'Institut de France) folio 74 recto

Codex A (Manuscrits de l'Institut de France) folio 43 verso

Codex Arundel folio 43v

Codex Arundel folio 54r

Codex Arundel folio 184v

²² Codex Leicester fol.29 v. (translation Theresa Wells)

²³ Windsor, RL 19116f, this folio is commented by Mory Gharib, Martin Kemp D. Kremers, M.M. Koochesfahani, "Leonardo's vision of flow Visualisation" in *Experiments in fluids*, n°33 (1), 2002, pp.219-223.

²⁴ Madrid Codex II, folio 147v.