The Body of the Architect. Flesh, Bones and Forces between Mechanical and Architectural Theories

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ABSTRACT: During the Renaissance, a revival of the Aristotelian writings on animal motion took place, which started contributing to a research trend where anatomical, physiological and mechanical notions intertwine. In their works, architects of the same period devoted themselves to understanding similar "body equilibria" in relation to the *imitatio naturae,* in accordance to its twofold meaning of *imitatio arborum* and *imitatio corporum.* Architecture and biomechanics thus found mutual contact points whenever static considerations on buildings played an essential role in the new *scientia aedificandi.* The current study revisits some stages of this process, with which architectural and mechanical theories provided new interpretative tools for builders. Bones, muscles and tendons became elements of mechanical models through which an attempt is made to create a dialogue between the *science des architectes* and the *science des ingénieurs*, before the two sciences resolved into a final separation.

INTRODUCTION

In the course of its history, architecture has always been accompanied by considerations on *imitatio naturae,* a subject which historians have dealt with from a number of viewpoints. In the twentieth century, architects and engineers repeatedly underlined the ties and relationships between architecture and nature by resuming ideas that had been known since antiquity. At the start of the century, two volumes, one published shortly after the other, opened a particularly appealing door to architects: Theodore Andrea Cook's *The curves of life* (Cook 1914) and Wentworth D'Arcy Thompson's *On growth and form* (Thompson 1917). Many researchers later elaborated on the ideas these books had suggested. For instance, the research group led by Frei Otto did so by means of a series of publications that later became famous, developed in the realm of the *Institut für leichte Flächentragwerke* (which he founded in Stuttgart in 1964), and Paolo Portoghesi with the book *Nature and architecture* (Portoghesi 2000). This branch of research kept feeding architectonic literature, and has done so especially in recent years, partly on the success wave of bio-architecture.

Until today, in this diverse research field, what has been missing as far the *imitatio corporum* is concerned is a historical analysis of the relationship between mechanics and architecture. Some stages of this 'natural history' of structural mechanics will later be introduced by this document, with the aim of offering elements for further investigations, on the frontline of both mechanical and architectural history. A starting question would be: what routes do body mechanics, whether human or animal, follow in order to become structural mechanics and vice versa, in a continuous role swap which took place on the building site and elsewhere between machine-as-body and architecture-as-body? Amongst all possible investigation routes, the author hereby chooses to follow the path which originated from Aristotelian writings.

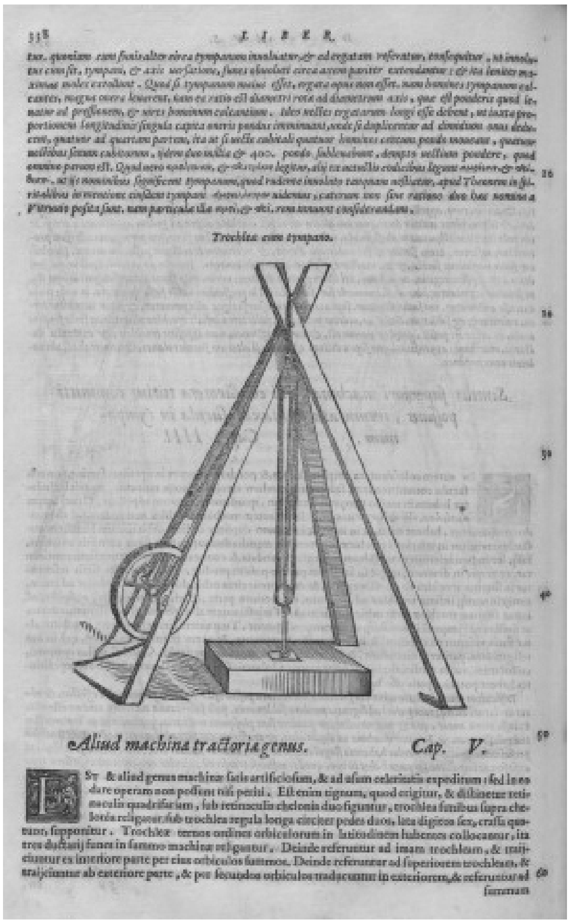
BODY-MACHINE-ARCHITECTURE

With time, a research trend developed around two works belonging to the Corpus Aristotelicum, known as *De motu animalium* and *De incessu animalium* (Aristotle [1937]) during the Renaissance, which gave birth to a number of disciplines that though very different from each other, have one distinctive element in common: the body. These two Aristotelian works deal with more general issues, but are above all a starting point for specific and circumscribed research on the following mechanical issues: the movement of body parts seen as

levers; the conditions of equilibrium of animal bodies in terms of centre of mass theory; the resistance of bones and limbs.
This research will later contribute to some familiar branches of medicine, ranging from anatomy to physiology, and will in the meantime play a part in the development of modern mechanics. Aristotle himself pointed in this direction:

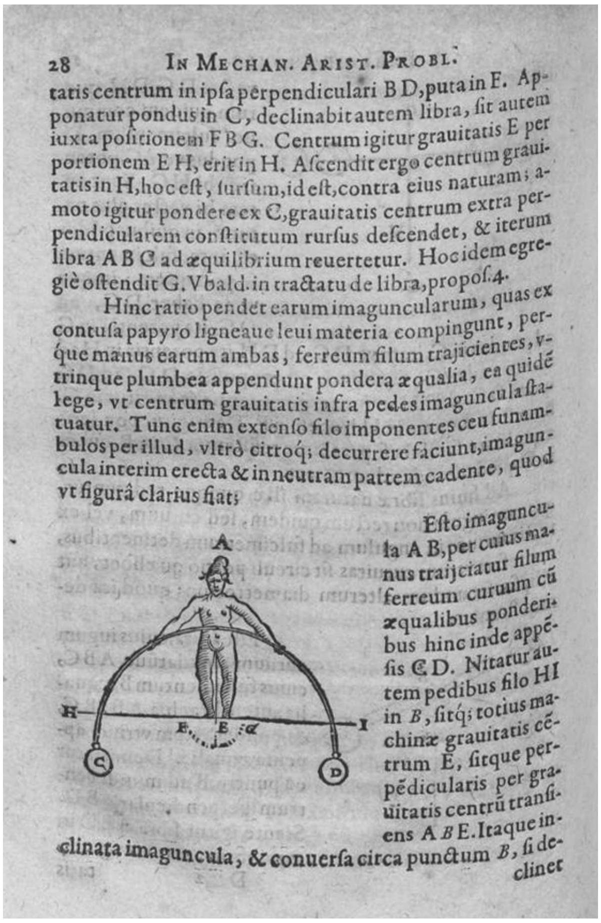
> The movements of animals resembles that of marionettes which move as the result of a small movement, when the strings are released and strike one another or a toy-carriage which the child that is riding upon it himself sets in motion in a straight direction, and which afterwards moves in a circle because its wheels are unequal, for the smaller wheel acts as a centre, as happens also in the cylinders. Animals have similar parts in their organs, namely, the growth of their sinews and bones, the latter corresponding to the pegs in the marionettes and the irons, while the sinews correspond to the strings, the setting free and loosening of which causes the movement. (Aristotle [1937], *De motu animalium*, VII)

Giovanni Alfonso Borelli's *De motu animalium* (Borelli 1680-81; English translation in Borelli [1989]), which already from the title states its explicit link to the antique Greek source, is a well known reinterpretation of the same theme within the "new science". Borelli clearly describes his objectives in the introduction to the book: "I undertook this work, not only to illustrate and enrich the part devoted to Physics by mathematical demonstrations but also to enlist Anatomy into Physics and Mathematics not less than Astronomy."
The relationship between mechanics and the body undoubtedly dates back to a remote past and the Aristotelian scripts must not have been isolated, even though the written evidence handed over to us is fragmented. For instance, Hippocrates writes about levers, wheels and cones in his volume *On fractures* (Hippocrates [1928]), where he describes the "lever methods" adopted to cure traumas. It is not by chance that these site tools are mentioned together with a description of human limbs and ways to overcome possible fractures. The text of the *Mechanical problems* (Aristotle [1936]), which belongs to the Aristotelian school, confirms this connection by alternating typical on-site issues (how wheels, levers and pulleys work) to questions on how the human body works. The Renaissance commentary to the *Mechanical problems* will later magnify this parallelism further, and will express what was probably already in the original intentions of the Greek author.
The *imitatio* and *interpretatio naturae* finds in machines and bodies a connection to contemporary daily life. The body seen as machine and the machine seen as body are a constant reference in all technical literature, up to our days. This is also shown by the medical analogy, so common in architectural literature, on the subject of analysis and the 'cure' of a building's 'disorders'. Construction sites are living organisms or can at least be traced back to living organisms by means of analogies.
These parallelisms take up a number of forms, which cannot easily be assimilated into one interpretative category. The body-architecture analogy can be found in the most obvious and well-known spheres – such as that of the human body as a measure for all things – to references that are more silent but no less significant, such as those that characterise technical jargon. In Italian (but the same can be said for other languages for analogous terms) the 'capra' (goat), for instance, refers to a site tool, (Fig. 1), the 'capriata', or truss, a term deriving from 'capra', a structure able to support loads, the 'incavallatura', often used as a synonym for 'capriata', refers to 'cavalli' (horses) *etc*.
In addition, with regard to push forces in vaults and the instabilities that follow, the architectonic language enters the world of an animal farm, and refers to the walls as being "kicked by donkey (or horse or mule) hooves". Even when the *imitatio* seems mostly an aesthetic-formal device (on this particular point, as known, architectonic literature is unlimited), there is no lack of precise mechanical-structural connotations. Throughout the Renaissance, these aspects are studied in architectural treaties, and become an integral part of the practice of architecture. While, on-site, pack animals and tools named after the animals are used, in built architecture the *imitatio* is related to a number of interpretative levels, always pointing towards mechanical significance. Let us think, for instance, about the bulge of columns, where, once again, the key term - *entasis* - most probably derives from a parallelism between mechanics and bodies: the widening of the column shaft seen as a stomach or as the swelling of a muscle under tension. Once again, it is Hippocrates the doctor to help clarify the terminology and to constitute the main linguistic source.
Theoretical mechanics follow a similar path, by never losing their interest for the body, looked into in all its mechanisms and all its potential. The previously mentioned Aristotelic works were assiduously commented upon in the course of the sixteenth and seventeenth centuries and became the pretext for considerations that inevitably involved architecture. The mechanical analysis carried out on bodies became a field of inspiration where considerations on the equilibrium of masses can be applied, and where the interest for the norm is tightly connected to a fascination for what is uncommon, anomalous, surprising. From this point of view, a strong relationship between theory and practice is established, in that both aspects are linked to the concept of wonder, which after all is at the root of the definition of mechanics themselves, seen as a discipline capable of explaining the wonders of machines.



Trochlea cum tympano.

Aliud machinæ tractoriæ genus. Cap. V.



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tatis centrum in ipſa perpendiculari B D, puta in F. Apponatur pondus in C, declinabit autem libra, ſit autem iuxta poſitionem F B G. Centrum igitur grauitatis E per portionem E H, erit in H. Aſcendit ergo centrum grauitatis in H, hoc eſt, ſurſum, id eſt, contra eius naturam; amoto igitur pondere ex C, grauitatis centrum extra perpendicularem conſtitutum rurſus deſcendet, & iterum libra A B C ad æquilibrium reuertetur. Hoc idem egregiè oſtendit G. Vbald. in tractatu de libra, propoſ. 4.

Hinc ratio pendet earum imaguncularum, quas ex contuſa papyro ligneaue leui materia compingunt, perque manus earum ambas, ferreum filum trajicientes, vtrinque plumbea appendunt pondera æqualia, ea quidē lege, vt centrum grauitatis infra pedes imaguncula ſtatuatur. Tunc enim extenſo filo imponentes ceu funambulos per illud, vltrò citroq; decurrere faciunt, imaguncula interim erecta & in neutram partem cadente, quod vt figurâ clarius fiat;

Eſto imaguncula A B, per cuius manus traijciatur filum ferreum curuum cū æqualibus ponderibus hinc inde appēſis C D. Nitatur autem pedibus filo H I in *B*, ſitq; totius machinæ grauitatis cētrum E, ſitque perpēdicularis per grauitatis centrū tranſiens A *B* E. Itaque inclinata imaguncula, & conuerſa circa punctum *B*, ſi declinet

Figures 1-2: from (Barbaro 1567), left, and (Baldi 1621), right

As far as practical matters are concerned, this wonder cannot be considered independently from the physicality of experience. The effective synthesis of these linguistic footprints is the image of the acrobat (Fig. 2). The latter becomes a commonplace in writings on mechanical problems, and static analysis related to human and animal bodies soon became a pretext for finding and elaborating on interesting parts of structural mechanics.

Though written references on this subject matter are few and sporadic, they are of great significance. In the Renaissance alone, it suffices to mention Leon Battista Alberti and his precise descriptions of construction in terms of bones, flesh and nerves that belong to the *De re aedificatoria* (Alberti 1485). Another instance are Leonardo's manuscripts and his research on mechanics and on the equilibrium of bodies, where parallelisms with the body of architecture are made explicit. Leonardo explains that without knowing the rules of those equilibria, the painter or the sculptor will be prevented from painting or sculpting, by being unable to make the movements or the images that are represented (whether human or animal) seem natural. Other artists of the same period focused on similar problems.With Teofilo Gallaccini (author of the well-known *Trattato sopra gli errori degli architetti*) body mechanics became the focal point of research. In the *Perigonia, overo degli angoli* (Gallaccini 1590-1598 and Gallaccini 2003) he painstakingly describes the movements of the human body, and underlines the structure and the function of joints (Fig. 3).

Another meaningful example, which brings us closer to architecture, is a manuscript (Ms XIII.F.25, *Biblioteca Nazionale di Napoli*) which is not dated but was probably developed around the same time. As with the *Perigonia,* the pretext is the Aristotelic school's *Mechanical problems*, but in this case the digression towards architecture becomes rigorous and explicit. The equilibrium of an elderly man leaning on his stick or that of a man bending over to pick up an object is immediately associated to the statics of a column, a truss, a vault (Fig. 4). The author of this manuscript, Bernardino Baldi, was to further develop these points in his posthumously published volume *In mechanica Aristotelis problemata exercitationes* (Baldi, 1621), of which the handwritten notes can be seen as a preparatory draft.

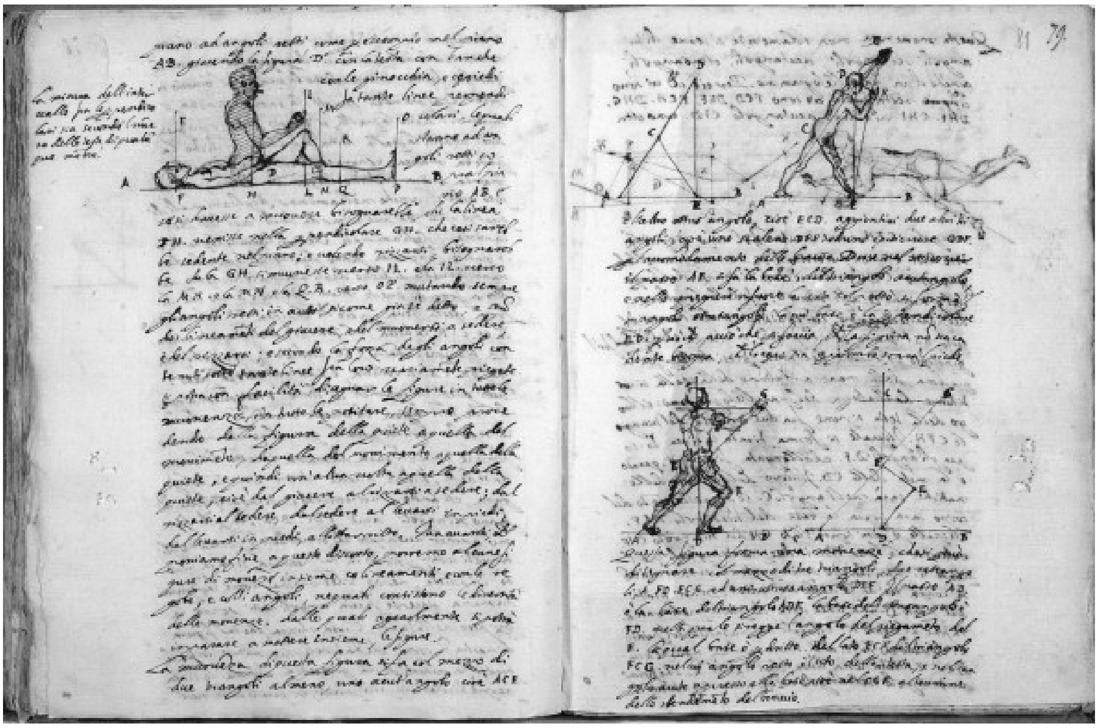
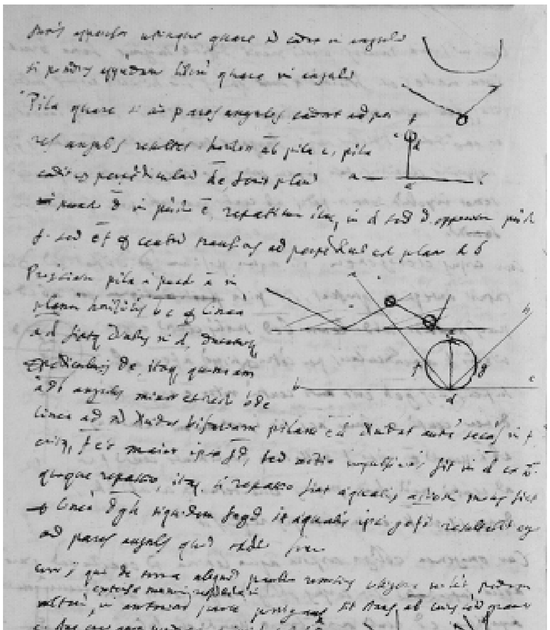


Figure 3: from (Gallaccini 1590-1598 ca.)



PARS II. DE POND. ET MENSVR. LIB. I. CAP. VI. 323

PROPOSITIO IX.

NVLLVS homo poterit se inclinare, aut in anteriorem aut in posteriorem partem, aut ad latera, quin linea directionis transiens per extremam partem quantitatis, cui innititur ex ea parte, in quam se inclinat, transeat etiam per centrum grauitatis corporis, aut hoc immineat quantitati, cui innititur: nam si extra illam maneat, cadet.

FIGVRA ABCD, sit dextro pedi B, insistens, quae in dextram partem D, inclinet se. Dico necessarium esse, ne cadat, lineam directionis transeuntem per extremum pedis B, versus pollicem transire per centrum grauitatis, vel vt dimittat illud ex parte pedis in posteriorem figurae partem: nam si centrum maneat in anteriori parte, absque dubio cadet, vt suprà [a] ostensum est. Huic igitur necessitati prouidit natura, docens hominem, cùm se inclinat, vt dixi, sinistrum pedem in posteriorem partem extendere, qui quasi vectis in statera praeponderet capiti: neque id tantummodo plerumque sufficit, praesertim si ad terram vsque inclinare se velit homo; sed etiam cum pede corporis partem posteriorem sensim retrahit, quoniam, vt dixi, stare non poterit, nisi aut linea directionis per centrum grauitatis transeat, aut saltem dimittat illud ex parte opposita ei, in quam se inclinat.

a 7. huius.

SCHOLIVM.

NEQVE verò huic etiam propositioni deerit modus, quo experiri quis possit ea, quae proponit, vera esse. Nam si quis vtrumque pedem coniunctum ac totum corpus muro cuicumque erecto ab eo auersus adaptet, atque inferiori parte muro coniuncta manente, sese in anteriorem partem inclinare velit, cadet. indeque discet hominem quodam naturali instinctu ductum quoties se inclinat, illa praestare quae diximus; quae quia impeditus à muro praestare non potest, cadit.

PROPOSITIO X.

QVOTIESCVMQVE homo sedet vt se erigat, necessarium est, vt pedes sedi quàm maximè habeat propinquos, caputque in anteriora educat.

HAEC omnia eueniunt, quòd dum homo sedet, sedi insistit, atque sedili erigit superiorem corporis partem, quae eminet; crura enim & reliquam corporis partem, quae pendet, non opus est vt dirigat. At postquam pedibus insistere cupit, necessarium est, vt totius corporis centrum grauitatis quàm maximè sit propinquum lineae directionis, quae transeat per pedes, quibus insistere vult: atque ideo corpori submittit pedes, caputque educit, vt pedibus ipsis immineat, adiutusque viribus naturalibus se erigit. ea verò quae ad lineam directionis spectant, ex suprà demonstratis manifesta sunt.

SCHOLIVM.

HVIVS propositionis praxim experietur facilè vniusquisque, si lento nimis gradu se erigit; quoniam motus velocitas & impetus nonnulla ex his praeuenit, alia ne facilè sensu percipiantur efficit.

PROPOSITIO XI.

NVLLVS homo, qui totus extensus supinus iaceat, se eriget ita vt erat extensus, quin cadat; sed necessarium est ei, vt corpus complicet, & superiorem partem corporis priùs erigat, ac pedes corpori submittat, & sic se eriget. Quod si iaceat pronus, manibus primùm innitatur simul ac pedibus, mox genua in anteriorem partem complicabit, atque ita se eriget.

QVANDO totus homo iacet, secundum omnes corporis sui partes consistit, atque adeo linea directionis non indiget. At verò cùm pedibus insistere vult, qui maximè sunt remoti à centro grauitatis corporis, oportet vt eos paulatim ad se colligat, ac priùs caput erigat, & corpus, mox illa praesterquae sedenti necessaria sunt, [a] vt se erigat. Quod verò ad secundam propositionis partem spectat, sequenti problemate, quo de quadrupedum insistentia & motu tractamus, manifestum erit.

a Superiore prop.

SCHOLIVM PRIMVM.

HVIVS propositionis tam nota est experientia, vt explicatione non indigeat.

SCHOLIVM SECVNDVM.

PRAECEDENTIVM propositionum argumentis aduersari videntur ea, quae à funambulis & alijs ioculatoribus fieri passim videmus: ipsi enim nonnumquam supini iacent, ac extensi se videntur erigere haud secus quàm si essent lignei. Ad quae respondebimus, omissis ijs, quae praestigijs ac malis artibus fiunt: de quibus non est nobis modò dicendum; duo praeterea consideranda sunt, in horum similibus motibus. Primùm velocitas motus, in qua ita sunt exercitati, vt in admirationem non modicam rapiant praesentes. Atque iccirco quamuis hos motus, quos dixi, aliqua saltem ex parte obseruent; tamen à nullo spectantium percipi possunt. Non enim possumus tam veloces esse visu, quàm hi sunt motu. Quamuis enim visus omnium sensuum ac motuum velocissimus esse videatur, tamen quoniam quandam exigit attentionem, qua percipiantur ea, quae oculis obijciuntur, ideo veloces motus oculorum aciem plerumque effugiunt. id quod experientia docemur: si enim quis regulam aliquam filo alligatam velociter circumducat, visum decipit, ac continuatam videtur conspicere rotam, haud secus quàm si regula esset simul in illis omnibus spacij partibus, quae pertransit, quoniam visus non potest tam citò aduertere, & videre illam in singulis.

Secundò etiam notandum est, plura hominem sua vi atque impetu in motu praestare posse, quàm quae grauium legibus coarctanda sint: ipse enim homo sibimet imprimit nonnumquam impetum, ita vt totum suum corpus & pondus erigat, in aere quoque erectus tantisper detinet sese, dum pedibus motus illos praestet saltantium, quas captiolas vulgò Hispani & Itali vocant. His igitur eisdem rationibus possunt hi, qui maximè exercitatione & viribus pollent, sibi aut eiusmodi imprimere impetum, quo plura ex ijs, quae diximus, suppleant. atque adeo nihil haec atque eiusmodi alia nobis aduersantur, qui de motu loquimur, & de animalium situ; quatenus grauia sunt atque perpendent; non verò quatenus viuentia sunt, aliisque motus atque a liis praestare possunt.

Tom. 3. Apparatus. Ee 2 PRO-

Figures 4-5: Ms XIII.F.25, l. 130 v, *Bibl. Nazionale di Napoli*, left, and from (Prado; Villalpando 1596-1605), right

In his monumental publication *In Ezechielem Explanationes* (Prado; Villalpando 1596-1605), edited with Jeronimo Prado, Juan Bautista Villapando seems to move along the same lines. In the third book, Villalpando inserts a section on mechanics (*De centro gravitatis, et linea directionis*), that puts forward one of the most original discussions on *centrobarica* of the time: a result of the architectural studies that Villalpando had made in Spain and the mathematical ones he had attended in Rome at the Collegio Romano, under the influence of Cristoforo Clavio's works. These pages were later read, amongst others, by Thomas Harriot, Marin Mersenne, Galileo Galilei, Paolo Casati, and became an important reference point in research in statics. It is no surprise that Villalpando himself, who had a great passion for architecture, was the one to have introduced so original a synthesis of the subject (Figs. 5-6).

Galileo himself is no stranger to these parallelisms, not only due to his studies on *De incessu animalium* and on mechanical problems, but also due to what he published in his *Discorsi e dimostrazioni matematiche* (Galilei 1638), the testament that encompasses embryonic studies that were never completed. Precisely at this point the discussion on the dimensions of the giant, introduced by means of a quotation from the "accortissimo poeta" - Ludovico Ariosto -, allows to make innovative considerations on the strength of materials, on structural optimisation and on the limits of scale analogies (Fig. 7).

In the seventeen hundreds this interest took on other forms, and classical literature stopped being directly referred to. This did not prevent the previously discussed themes from attracting researchers' attention. One example is found in John Theophilus Desaguliers' *A course of experimental philosophy* (Desaguliers 1734), where the body becomes the protagonist of mechanical interpretation, in particular of statics. Once again, architecture was introduced as a valid example of what had been shown theoretically and even in this anomalous case, what is exceptional starts to be part of scientific narration: an example is the acrobat, as we have seen in one of the previous images, but also a "German Strong Man" that exhibited at London fairs. Desaguliers thus unmasks and explains the 'mechanical' tricks of the modern Samson (Figs. 8-9).


524 APPARATVS VRBIS AC TEMPLI

PROPOSITIO XII.

QVADRVPEDIA tunc stabunt, cùm linea directionis per extremum superficiei, quam inter extremos pedum terminos operiunt, transiens pertransierit etiam per centrum grauitatis eorum, uel dimiserit illud ex parte superficiei, cui insistunt: ideoque cùm progrediuntur, si vtrumque dextrum pedum simul erigunt cadent, nisi linea directionis transiens per extremum reliquorum, transierit per centrum grauitatis, aut reliquerit illud ex parte pedum. At cùm sua corpora posterioribus tantum modo pedibus innixa erigunt; & poplites & magnam corporis partem à pedibus in posteriora retrahant necesse est, vt centrum grauitatis ad lineam directionis pedibus superimponant.

EQVVS ABCDE, cuius centrum grauitatis sit A, quattuor pedibus insistat BCDE; quantitas igitur cui insistit, habenda erit tota superficies BCDE. de qua philosophandum est iuxta demonstrata. At quoniam frequenter solent animalia ita se constituere insistentia, vt maximè consistere possint, fit vt linea directionis EA, per medium quantitatis, cui insistunt, G, transiens se extendat ad centrum grauitatis A. Atque adeo cùm incedit, si à terra simul subleuet vtrumque dextrum pedem BE, cadet equus, nisi linea directionis per pedem C, transiens, transeat etiam per centrum grauitatis. quod suprà demonstratum est. Ac tandem si se erigat equus, ea praestat, quae in extrema propositionis parte proposuimus, & in apposita figura quiuis obseruare poterit.

Sup. 7. huius.

COROLLARIVM.

EX dictis fit manifesta ratio, propter quam equitantes moueamur, non tantùm iuxta progressum equi, verùm etiam alijs atque alijs motibus, quibus nonnumquam vehementer nos concuti experimur: nam vt dixi, eiusmodi motus omnes nunc ad latus sinistrum, mox ad dextrum, deinde ad sinistrum, vt sua pondera libret equus, sunt necessarij. Vehementiores autem, atque molestiores eos esse in diuersis equis motus experimur, qui quare diuersi sint, si examinare velimus, habenda nobis ratio est, virium, velocitatis motus, atque exercitationis: vsu enim ac disciplina alijs atque alijs moribus bruta ipsa animantia imbuuntur.

PROPOSITIO XIII.

AVIVM, cùm pedibus insistunt, eadem quae de bipedibus habenda ratio est. Cùm verò volant, quoniam alis suspenduntur, necessarium est, vt linea directionis per alarum medium transiens, transeat etiam per grauitatis centrum.

HAEC omnia, quae de auium insistentia, & motu proponimus, manifestè ex antecedentibus demonstrantur: nam quae in priori parte dicenda essent, ea omnia communia hominum insistentiae sunt; eo tamen excepto, quòd homines, qui semper exstant, raròque in anteriorem partem se inclinant, duplici & altera alteri contraria complicatione flectuntur, vtpote qui genua complicant antrorsum, complexas retrorsum: at aues, quae caput & corpus ad manducandum semper inclinant, crura retrorsum complicant, vt linea directionis per pedes transiens, transeat etiam per centrum grauitatis; quod exemplis fiet manifestum. Sit enim auis AB, cuius centrum C, insistens pedibus D, cùm caput inclinat, necessarium est, vt crura E, retrorsum complicet, vt linea directionis DC, per medium pedum, quibus auis insistit, transiens transeat etiam per centrum C. id quod quilibet poterit quotidie obseruare. Quod verò ad secundam partem spectat, cùm auis volans, duabus alis quasi fulcris sustineatur, ne totum corpus in anteriorem, aut posteriorem partem praeponderans inclinet, necessarium est, vt pondus corporis ex aequo libretur: quod non fiet, nisi linea directionis per fulcrum, & centrum grauitatis transeat. Huiusmodi autem auium indigentiae prouidisse videtur natura, quae auibus, quarum ob alias atque alias causas colla decuit esse longiora, crura dedit etiam longiora, vt his atque illis pariter extensis, vtrimque ex aequo ponderarent. Aliud quoque librandi genus volucres à natura edoctae sunt. Nam cùm anteriorem corporis partem sursum eleuare volunt, & posteriorem deprimere, alas, hoc est, fulcra, quibus sustinentur, in anteriorem partem extendunt: cùm verò contrà inferiùs suum volatum dirigunt, in posteriorem partem alas retrahunt; hoc enim vel illo modo facilè efficiunt, vt grauitatis centrum saltem in volantium corpore loco mutetur. Eadem ratione ab ea parte, quae propendet, alas retrahentes, aequa trutina aues seipsas librare consueuerunt. id enim faciunt, quod faceret, qui ab axe, cui insistit statera, pondus remoueret, aut si axem remoueret à pondere; vtraque enim pariter ratione pondus aequiponderaret. Sed de viuentibus iam satis, ad plantas & inanimata examinanda accingamur.

PROPOSITIO XIIII.

ARBORES, plantae, & herbae nisi impediantur, ad angulos rectos se erigunt; non quidem pauimenti, cui insistunt, sed horizontis, nempe secundum directionis lineam, per trunci ima ad grauitatis centrum deductam.

IN accliui latere ABC, montis ABCD, ducatur recta AC, ex cuius puncto B, erigatur ipsi AC, perpendicularis BF, atque per idem punctum D, B, erigatur linea directionis DBE. Iam ex eodem puncto nascatur arbor BE, quam dico non posse stare, si iuxta rectitudinem lineae BF, nasceretur. Nam cùm tota arbor cum omnibus suis ramis & trunco nullum habeat fulcrum, cui innitatur, praeter quantitatem B, cui affixae sunt radices, ac non solùm centrum grauitatis arboris, verùm tota arbor propendeat extra lineam directionis DBE, cadet absque dubio, nisi aliunde aut teneatur aut fulciatur. Quapropter arbor nascetur horizonti recta, nempe iuxta lineam directionis DE.

Arbores rectae nascuntur vt stare possint.

Cuius rei rationem aliam quoque assignare possumus; quòd cùm arbor & truncus eò sint stabiliores quò directiores; naturaque eorum procreatrix arborem conseruari, ac maximè stare semper intendat, eidem rectitudinem praefiniuit lineae directionis. His etiam accedit, arbores ac plantas, quod calorem & vitam à caelo & sideribus expetant, naturali quasi motu in caelum ferri. quod ipsa quoque experientia compertum est: arbores enim, quae in opacis locis nascuntur, prae ceteris eiusdem generis altiùs surgunt, quò Solem, vt fertur, exquirant. At naturalis motus non impeditus semper est rectus (exemplo sunt grauia omnia & leuia) ex quo fit vt arbores secundum directionis lineam sursum erigantur. Atque hoc ipsum, quod de arboribus & plantis diximus, de herbis etiam intelligemus, maiori prorsus earundem indigentia permoti: nam quò teneriores sunt, & subtiliores earum calami, eò magis oportuit rectitudine fulciri, cùm minori etiam pondere pressae rumpantur. Excipimus ab his tamen, vitem, cucurbitam, hederam, portulacam, atque his similes, quae caulis debilitate seipsas rectâ non possunt sustinere.

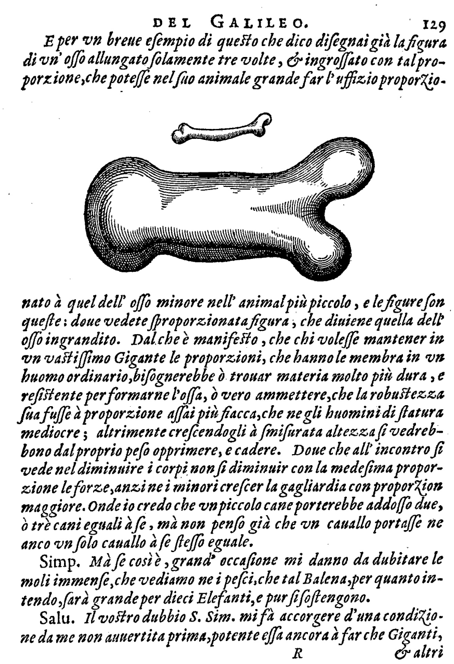
Rectitudinem arboribus natura praescribit, eas maximè conseruari volens.

Arbores rectà in caelum tendunt, vnde calorem & vitam suscipiunt.

Naturalis motus non impeditus semper est rectus.

Plantae & herbae magis egent rectitudine.

EXA-


DEL GALILEO. 129

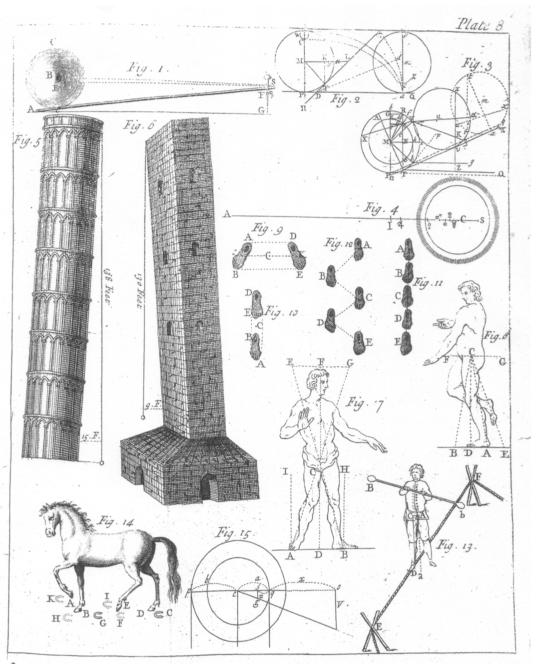
E per vn breue esempio di questo che dico disegnai già la figura di vn' osso allungato solamente tre volte, & ingrossato con tal proporzione, che potesse nel suo animale grande far l'uffizio proporzionato à quel dell' osso minore nell' animal più piccolo, e le figure son queste: doue vedete sproporzionata figura, che diuiene quella dell' osso ingrandito. Dal che è manifesto, che chi volesse mantener in vn vastissimo Gigante le proporzioni, che hanno le membra in vn huomo ordinario, bisognerebbe ò trouar materia molto più dura, e resistente per formarne l'ossa, ò vero ammettere, che la robustezza sua fusse à proporzione assai più fiacca, che ne gli huomini di statura mediocre; altrimente crescendogli à smisurata altezza si vedrebbono dal proprio peso opprimere, e cadere. Doue che all' incontro si vede nel diminuire i corpi non si diminuir con la medesima proporzione le forze, anzi ne i minori crescer la gagliardia con proporzion maggiore. Onde io credo che vn piccolo cane porterebbe addosso due, ò trè cani eguali à se, mà non penso già che vn cauallo portasse ne anco vn solo cauallo à se stesso eguale.

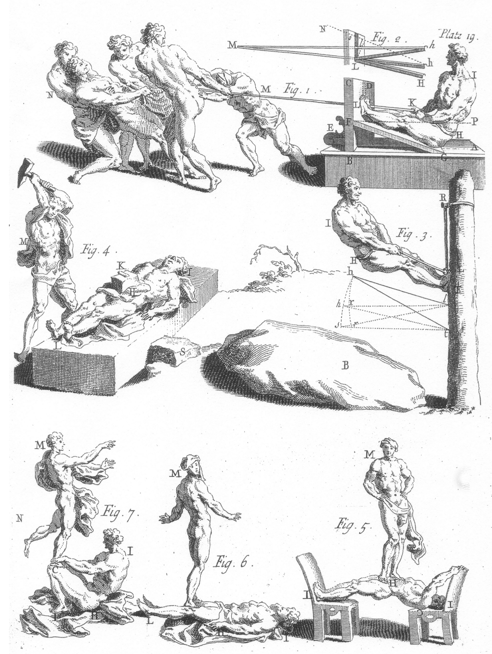
Simp. *Mà se così è, grand' occasione mi danno da dubitare le moli immense, che vediamo ne i pesci, che tal Balena, per quanto intendo, sarà grande per dieci Elefanti, e pur si sostengono.*

Salu. *Il vostro dubbio S. Sim. mi fà accorgere d'una condizione da me non auuertita prima, potente essa ancora à far che Giganti, & altri*

R

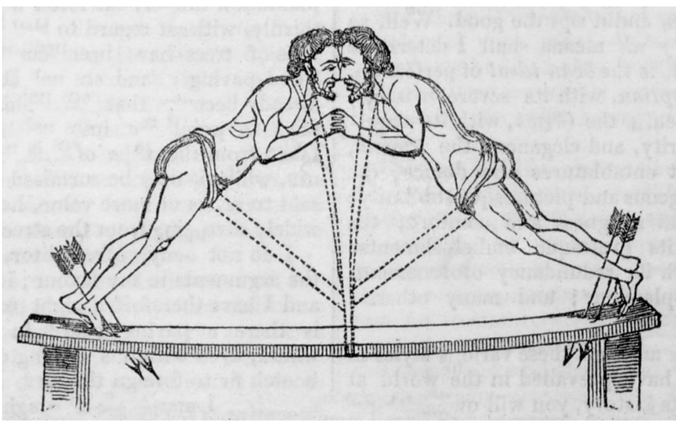
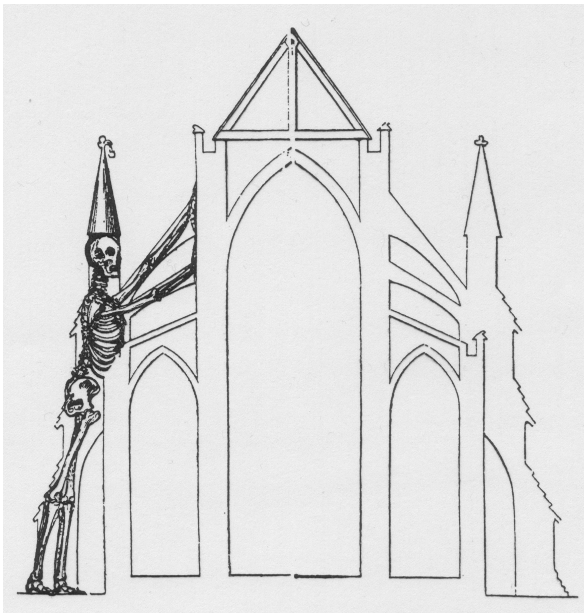
Figures 6-7: from (Prado; Villalpando 1596-1605), left, and (Galilei 1638), right





Figures 8-9: from (Desaguliers 1734)

Desaguliers himself was very well known in London for the private lessons he held, often in his Channel Row laboratory-house, for those who had no expertise in mathematics or geometry, but nevertheless wanted to be informed on the 'new science'. This trend is known to have had a following which lasted until present days, and to have fed a particular branch of literature between mechanics and architecture. The texts belonging to this trend made an attempt to bring architects ignorant of mathematics and rational mechanics closer to the 'mechanics for architecture', after programmatic pamphlets, such as Charles-François Viel's writings, had attacked the modern *science des ingénieurs* and its preference for new construction materials. A *science des ingénieurs* that in the first half of the Nineteenth century was consolidating its physical and mathematical apparatus - formalised by means of Cauchy's, Navier's, Saint-Venant's contributions -, by emphasising the role of the mathematical theory of elasticity.
Structural mechanics, which had become more and more difficult for architects and more broadly for the large public of amateurs to understand, found in the *imitatio naturae* an interpretative short cut for immediate comprehension, a channel to keep alive a dialogue that seemed destined to stay mute forever, after the clear-cut distinction between educational paths. While the image of the architect and that of the engineer had a tendency to separate and grew apart, some took upon themselves the task of translating the mechanical functioning of buildings in an elementary and visually effective language. Images that had an immediate impact and required no hermeneutical effort were increasingly preferred to differential equations, to their numbers and symbols, that, by then, had started to govern all *mechanics of materials* and *structural mechanics* (i.e. the subjects that make up the technical knowledge of the *ingénieur polytechnique*), to the complex laboratory research and to the related mathematical theories, which allow the interpretation of the data obtained from those experiments.
This is what Alfred Bartholomew proposed in his *Specifications for practical architecture*, in the section entitled *On the mechanical trussing of building* (Bartholomew 1840, Part I, chap. 50). By means of a historical quotation (the fight between Ulisses and Ajax in the Iliad), Bartholomew introduces the mechanical problem of the truss, and illustrates it with images that require no comments (Fig. 10). The same applies to the *Dynamic knowledge of the gothic architects*, which Bartholomew also depicts with a delightfully anthropomorphic image (Fig. 11). This imaginative radiography of mechanical behaviour allowed the reader to skip in one jump all the formulae and diagrams that in the meantime had filled up the structural mechanics publications written by engineers and mathematicians.
The images of the *Specifications* meet one common need: that of explaining how the *gran macchina* of architecture works, by means of the sensorial experience related to the body and to its ability to perform mechanical tasks. Bartholomew translates the results of theory into pills of daily use, to be shown as program in the first pages of the treaty (Fig. 10 is included in the text, but also on the flyleaf of the volume).
The fact that in the same years even the most refined *art de l'ingénieur* was looking at the *imitatio naturae* with great interest should not be surprising. In the mid-sixties of the eighteen-hundreds, after having seen the spongy structure of trabecular bone that his anatomy-pathologist colleague Meyer was studying, Carl Culmann had an intuition on the analogy between the internal structure of the femur head and the distribution of the isostatic lines in the structural elements. Research studies on the *resistentia solidorum* therefore shift from Galileo's giant bone to the femur described by Culmann, one of the fathers of graphic statics, a discipline that Eugène Emmanuel Viollet-le-Duc and Antoni Gaudì will be particularly interested in.

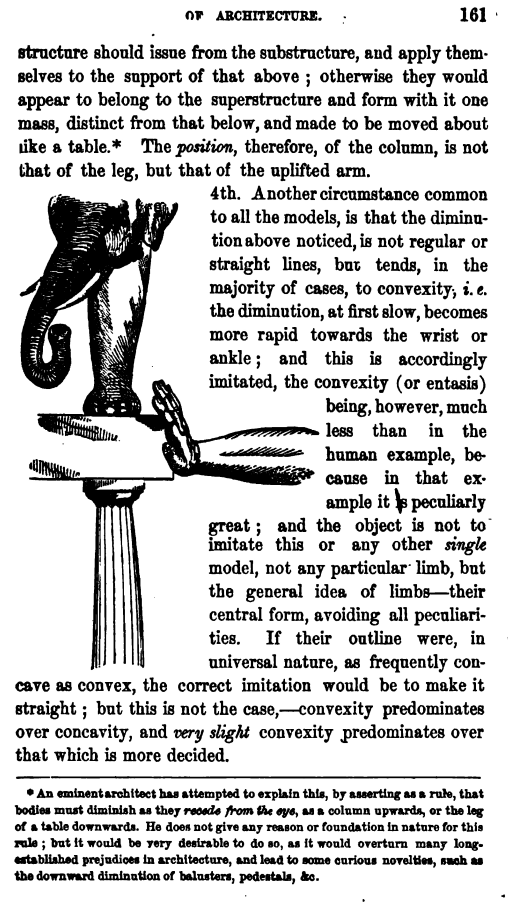



Figures 10-11: from (Bartholomew 1840)

Needless to say, the parallelisms between skull and dome that apply to Saint Peter's dome had been looked into in the sphere of the collaboration between Giovanni Battista Morgagni, famous doctor, and Giovanni Poleni, a physicist called upon to interpret the instability of the dome (Poleni 1748).
Over the Ocean, in the United States, a bizarre interpretation of the static equilibria in architecture can be found in Bullock's *The rudiments of architecture* volume (Bullock 1865), where the chapter on *imitatio* no longer dwells on the well known images to which renaissance and baroque literature was used to, but is coloured of an unusual exoticism (Fig. 12).

A CONCLUSIVE STARTING POINT

And it is here that the story should start, although due to space limitations, it has to stop instead. These ideas merely introduce a vast amount of 20th Century literature in which architects tried to find comfort and protection from the difficulties of the mathematical language. It is a body of literature that took upon itself the task of explaining to 'the people' that which, due to engineering tools, was no longer understandable by simply anyone. In the meantime, the *imitatio naturae* continued to form the imagery on which some famous constructors (architects and engineers) based their 'theories' (from Buckminster Fuller to Santiago Calatrava). These are merely two of many examples. When Le Corbusier had to describe the subject of *L'architecture et l'esprit mathématique* in the book edited by François Le Lionnais and entitled *Les grands courants de la pensée mathématique* (Le Corbusier 1948) it was the memory (was it authentic or was it made up later?) of a stay in the mountains that created a relationship with structural mechanics (Fig. 13). The leg of a chamois, by him dissected with care while looking for muscles and tendons, became the reference to the 'natural' mechanics of bodies and acted as a hint to the understanding of the architectural 'inventions' of the famous architect. "A chamois' leg and reinforced concrete pilotis are materials at work that create intense, agile, and intelligent balanced ensembles. Something to enchant the soul and dismay the conformists; and, finally, to repudiate Vignola!" (Le Corbusier 1948, p. 484).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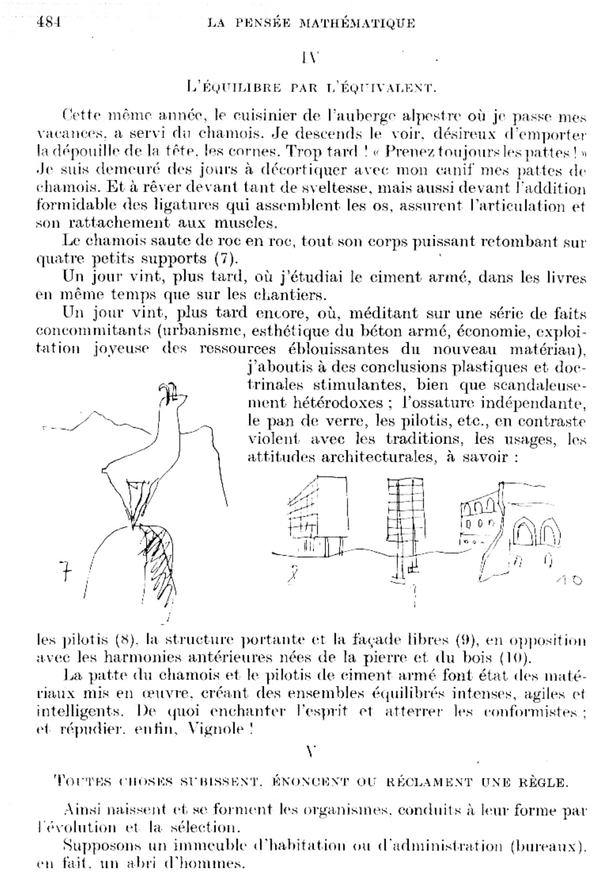
structure should issue from the substructure, and apply themselves to the support of that above ; otherwise they would appear to belong to the superstructure and form with it one mass, distinct from that below, and made to be moved about like a table.* The *position*, therefore, of the column, is not that of the leg, but that of the uplifted arm.

4th. Another circumstance common to all the models, is that the diminution above noticed, is not regular or straight lines, but tends, in the majority of cases, to convexity; *i. e.* the diminution, at first slow, becomes more rapid towards the wrist or ankle ; and this is accordingly imitated, the convexity (or entasis) being, however, much less than in the human example, because in that example it is peculiarly great ; and the object is not to imitate this or any other *single* model, not any particular limb, but the general idea of limbs—their central form, avoiding all peculiarities. If their outline were, in universal nature, as frequently concave as convex, the correct imitation would be to make it straight ; but this is not the case,—convexity predominates over concavity, and *very slight* convexity predominates over that which is more decided.

* An eminent architect has attempted to explain this, by asserting as a rule, that bodies must diminish as they *recede from the eye*, as a column upwards, or the leg of a table downwards. He does not give any reason or foundation in nature for this rule ; but it would be very desirable to do so, as it would overturn many long-established prejudices in architecture, and lead to some curious novelties, such as the downward diminution of balusters, pedestals, &c.


484 LA PENSÉE MATHÉMATIQUE

IV

L'ÉQUILIBRE PAR L'ÉQUIVALENT.

Cette même année, le cuisinier de l'auberge alpestre où je passe mes vacances, a servi du chamois. Je descends le voir, désireux d'emporter la dépouille de la tête, les cornes. Trop tard ! « Prenez toujours les pattes ! » Je suis demeuré des jours à décortiquer avec mon canif mes pattes de chamois. Et à rêver devant tant de sveltesse, mais aussi devant l'addition formidable des ligatures qui assemblent les os, assurent l'articulation et son rattachement aux muscles.

Le chamois saute de roc en roc, tout son corps puissant retombant sur quatre petits supports (7).

Un jour vint, plus tard, où j'étudiai le ciment armé, dans les livres en même temps que sur les chantiers.

Un jour vint, plus tard encore, où, méditant sur une série de faits concommitants (urbanisme, esthétique du béton armé, économie, exploitation joyeuse des ressources éblouissantes du nouveau matériau), j'aboutis à des conclusions plastiques et doctrinales stimulantes, bien que scandaleusement hétérodoxes ; l'ossature indépendante, le pan de verre, les pilotis, etc., en contraste violent avec les traditions, les usages, les attitudes architecturales, à savoir :

les pilotis (8), la structure portante et la façade libres (9), en opposition avec les harmonies antérieures nées de la pierre et du bois (10).

La patte du chamois et le pilotis de ciment armé font état des matériaux mis en œuvre, créant des ensembles équilibrés intenses, agiles et intelligents. De quoi enchanter l'esprit et atterrer les conformistes ; et répudier, enfin, Vignole !

V

TOUTES CHOSES SUBISSENT, ÉNONCENT OU RÉCLAMENT UNE RÈGLE.

Ainsi naissent et se forment les organismes, conduits à leur forme par l'évolution et la sélection.

Supposons un immeuble d'habitation ou d'administration (bureaux), en fait, un abri d'hommes.

Figures 12-13: from (Bullock 1865), left, and (Le Corbusier 1948), right

A few years later, another French architect explained this 'hidden' relationship, that of the intrinsic analogy whose influences are felt through unforeseen ways, better than anyone else. In this instance, the poetic voice is able to make the mechanical idea visible without turning to the charm of images attached to a text. This was a step that deserves to be read whole and that follows a question raised earlier in the text: "How do these masters know in advance that a building designed in that way won't collapse?". And here is the answer, entrusted to whom was leading the construction of the Thoronet abbey, in Provence:

That man will be everything: clay and sand, stone and wood, iron and bronze. He will integrate, identify himself with every material, every element, every external and internal stress. Thus he will carry them, estimate them, sound them, see them with his very soul as though he held them in his hands. These presumptions are not metaphors; I deny any poetic intention. I am asserting material facts which for me are indisputable. I think of them prosaically. If I am a wooden beam placed between two supports twenty feet apart, I estimate the resistance of my fibrous loins, and I thicken to attain the sectional dimension that will enable me to resist the flection entailed by my own weight and that which I am to carry. At the same time I think of my outward appearance, my trajectory's visual effect and my colour: in this way I decide what I am to be made of, oak or spruce. All this process is going on during the time when I am thinking creatively in plastic terms: it is a parallel activity. The elementary example I have just described applies to all contingencies; the beam is a simplified image for the flying buttress and its light structure, for the solid buttress and for the arch. I can and must divide myself into the stones of an arch, feel myself to be keystone, breast, summer or simple arch-stone, know the stone in my flesh, look on it as my own skin, make it follow the chosen line and the nascent volume. The form will be justified by the choices made. Structure is everything, form is everything, matter is everything. (Pouillon 1964, pp. 109-110, English translation in Pouillon 1970, pp. 102-103).

The words of Fernand Pouillon call upon us to retrace the story of *imitatio naturae* backwards: once again and deeper than before, between professionals and amateurs, within the body of the architect and architecture.

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