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PLANTS AND LABORATORIES: THE ASCENT OF SAP BETWEEN PHYSICS AND VEGETAL PHYSIOLOGY

by

FABRIZIO BALDASSARRI*

University Ca' Foscari of Venice/Indiana University, Bloomington, USA

The ascent of sap in plants represented a puzzle in early modern studies of nature. Although philosophers, gardeners and naturalists had traditionally explained it as a process of fermentation caused by the Sun, an alternative view emerged in combination with the physical studies of pressure. This latter field of experimentation somehow influenced the study of plants. While the mathematical study of liquids gained momentum, scholars started to apply these rules to vegetal processes, comparing pipes with plant vessels and making plants the objects of their laboratory. In this article, I explore the various ways in which scholars dealt with this phenomenon, following the physics of the equilibrium and motion of liquids, and especially through the two alternative interpretations—one developing in Italy, and one north of the Alps—that characterized the seventeenth-century study of liquids. I focus on Nehemiah Grew's and Marcello Malpighi's different interpretations of the ascent of sap in plants, as they were two major actors in seventeenth-century botanical studies, and how much they drew their interpretations from experiments in the laboratory.

Keywords: plant studies, physics, hydrostatics, ascent of sap, capillarity, pressure, fermentation, Digby, Boyle, Hooke, Grew, Borelli, Accademia del Cimento, Malpighi

> Let us see whether this ascension occurs passively
> due to the attraction of heat, or actively, because matter in itself
> possesses an intrinsic principle to escape from the centre and rise up.
> (Torricelli, *Lezioni accademiche* (Silvestri, Milano, 1823), p. 138.)

In 1661 Robert Hooke (1635–1703) discussed the capillary action on which he had worked with Robert Boyle (1627–1691), disclosing a meaningful insight.[1] He speculated that the study of pressure had implications in the explanation of the physiology of living bodies, as

*fabrizio.baldassarri@unive.it

1 On hydrostatics in the seventeenth century, see Alan F. Chalmers, 'Qualitative novelty in seventeenth-century science: hydrostatics from Stevin to Pascal', *Stud. Hist. Phil. Sci. A* **51**, 1–10 (2015); and Alan F. Chalmers, 'Hydrostatics in the seventeenth century', in *Encyclopedia of early modern philosophy and the sciences* (ed. Dana Jalobeanu and Charles T. Wolfe), pp. 873–881 (Springer, Cham, 2022).

being perhaps involved in some of their processes.[2] Accordingly, 'there will be divers *Phaenomena* explicable thereby, as, the Rising of Liquors in a Filtre […] perhaps also the ascending of the Sap in Trees and Plants, through their small and some of them imperceptible Pores (of which perhaps I may say more on another occasion) at least the passing of it out of the earth into their roots'.[3] It appears neither Hooke nor Boyle appealed to fermentation, namely, to the role of the Sun in raising liquids in plants. This was, however, a common feature: earlier natural philosophers, such as Francis Bacon (1561–1626), René Descartes (1596–1650), Pierre Gassendi (1592–1655), Henricus Regius (1598–1679) and Kenelm Digby (1603–1665), had, in fact, made an appeal to fermentation and to the role of the Sun, as well as to some internal spirits, appetites or powers to account for the rise of water in plants. At the same time, this also was a matter of hydraulics and waterworks that had attracted the attention of scholars at large, but also gardeners and experimenters, who mostly referred to hydraulics to construct waterworks or to ease garden irrigation and landscape—for instance, in a note dated 30 September 1663, Hooke presents an apparatus for fetching up water from any depth of the sea.

An interplay between machines and plants emerges in Digby's *Two treatises* (1644), where he compared plants to the hydraulic engine he might have observed in Toledo, the so-called *Artificio de Juanelo Turriano*, stressing that plants' functioning mostly consisted of raising water similarly to the Spanish engine, but he did not engage with this phenomenon any further.[4] Still, this was a mere analogy between plants and engines or machines, whereas a clear engagement of the rise of sap by means of the laws of hydraulics did not emerge. In contrast, Hooke and Boyle seemed to imply that the study of pressures and hydrostatics that mainly belong to physics and to their experiential practice in laboratories may shed light on the ascent of sap in plants. This claim unveils a possible relation between physics and the study of living nature, that is, the study of the equilibrium and motion of liquids with the movement and circulation of fluids in living bodies, and especially in plants.

This seems to entail another issue, voiced by Torricelli in the incipit: if the ascent of sap is due to the Sun, the fermentation is an external source and it occurs passively in plants, whereas if it is due to an intrinsic activity it may reveal plants as performing actions. Investigating this issue thus became crucial to understand plants in their own right and distance them from being merely analogous to animals or machines.[5] Experimenting with vegetal bodies might shed new light on plant science.

However, neither Hooke nor Boyle had performed such observations, despite Hooke's stressing the pertinence of capillary action for the ascent of sap again in *Micrographia*

2 Cf. David Deming, 'Robert Hooke's contributions to hydrogeology', *Groundwater* **57** (1), 177–184, at p. 179 (2019).

3 Robert Hooke, *An attempt for the explication of the phaenomena, observable in an experiment published by the honourable Robert Boyle …* (J.H. for Sam Thomson, London, 1661), p. 26.

4 Kenelm Digby, *Two treatises. In one of which the nature of bodies; in the other the nature of mans soule is looked into* (Blaizot, Paris, 1644), pp. 207–208. See Antonio Clericuzio, 'Digby on plant and palingenesis', in *The philosophy of Kenelm Digby (1603–1665)* (ed. Laura Georgescu and Han Thomas Adrianssen), pp. 163–181 (Springer, Cham, 2022). On the rich interplay concerning both architectural or engineering business and animal and plant anatomies, see Domenico Bertoloni Meli, *Thinking with objects: the transformation of mechanics in the seventeenth century* (Johns Hopkins University Press, Baltimore, 2006), p. 95.

5 On the importance of the movement of sap in plants and its comparison to blood circulation in the seventeenth century, see François Delaporte, *Nature's second Kingdom* (trans. A. Goldhammer) (MIT Press, Cambridge MA, 1982). See also, Fabrizio Baldassarri, 'From the analogy with animals to the anatomy of plants in medicine: the physiology of living processes from Harvey to Malpighi', in *Plants in 16th and 17th century: botany between medicine and science* (ed. Fabrizio Baldassarri), pp. 121–144 (De Gruyter, Berlin, 2023).

(1665).[6] In this text, Hooke discussed a few specific phenomena occurring in plants, which he had observed and performed in laboratories. For instance, he had observed the sensitive plants in the garden of Mr Chissin in St James's Park, as he proposed a mechanical explanation based on the pressure of fluid moving in it, therefore reducing this phenomenon to the physics of liquids, but without performing any experiment to confirm his claim.[7] A different case concerns the stinging point of nettles, as Hooke described the mechanics of irritation of stinging apparatuses functioning like syringes, both injuring and injecting a fluid. He claims to have observed the movement up and down of a liquor in nettles, 'a *Phaenomenon* as plain as I could ever see a parcel of water ascend and descend in a pipe of Glass'.[8] In claiming to have observed the movement in nettles as he saw it in pipes, Hooke thus claims one could explain the vegetal phenomenon by means of a laboratorial investigation, and the mechanics of irritation could be reduced to the movement of liquids in alembics. Similarly, in the case of the beard of wild oats, Hooke realized that it consists of two filaments twisted together, and the microscopic observations inspired him to devise a new instrument to measure humidity, a hygroscope.[9] In this case, he used plants (and a dial) as philosophical instruments of a laboratory.[10] Plants slowly but significantly enter the physical laboratory.

A particularly striking case is the rise of water, which defies the force of gravity and presents several problems in seventeenth-century studies. As Domenico Bertoloni Meli has noted, in the second half of the seventeenth century, the mathematical study of liquids, notably water and other incompressible fluids, gained momentum. While it was at the centre of a lively debate, scholars turned to plants, and, consistent with Hooke's insight, addressed the questions related to the ascent of sap in vegetation from a more physically-informed perspective, following the physics of the equilibrium and motion of liquids.

In this article, I investigate the specific case of liquids moving within plants. First, I concentrate on the accounts for the motion of sap as a fermentation caused by the Sun, which developed in horticultural experiments and was widespread in philosophical interpretations of plants. Then, I discuss the growing attraction of the Royal Society to the ascent of sap as scholars approached plants as laboratory pipes, in which they could test the physical causes of the movement of liquids.[11] Finally, I examine the studies of Nehemiah Grew (1641–1712) and Marcello Malpighi (1628–1694), two of the most important naturalists working with plant anatomy and physiology in the late seventeenth century, who observed plants in laboratories and also combined physical knowledge with vegetal physiology—these authors followed the 'two types of approach, one based on motion and the other on statics'[12] that widely characterized the seventeenth-century study of liquids, revealing how much this was not a chance study but was scientifically grounded.

6 Robert Hooke, *Micrographia: or some physiological description of minute bodies made by magnifying glasses* (J. Martyn and J. Allestry, London, 1665), pp. 10, 20–21, 28.

7 *Ibid.*, pp. 116–121. Cf. Domenico Bertoloni Meli, *Mechanism, experiment, disease: Marcello Malpighi and seventeenth-century anatomy* (Johns Hopkins University Press, Baltimore, 2011), p. 235.

8 Hooke, *op. cit.* (note 6), p. 143. Cf. Domenico Bertoloni Meli, *Mechanism: a visual, lexical and conceptual history* (University of Pittsburgh Press, Pittsburgh, 2019), p. 70.

9 Bertoloni Meli, *op. cit.* (note 8), pp. 91–92.

10 On philosophical instruments, see Bertoloni Meli, *op. cit*. (note 4), pp. 3–4.

11 Beryl Hartley, 'Exploring and communicating knowledge of trees in the early Royal Society', *Notes Rec. R. Soc. Lond.* **64**, 229–250 (2010).

12 Bertoloni Meli, *op. cit*. (note 4), p. 166.

The Sun, fermentation and the motion of sap according to philosophers, gardeners and naturalists

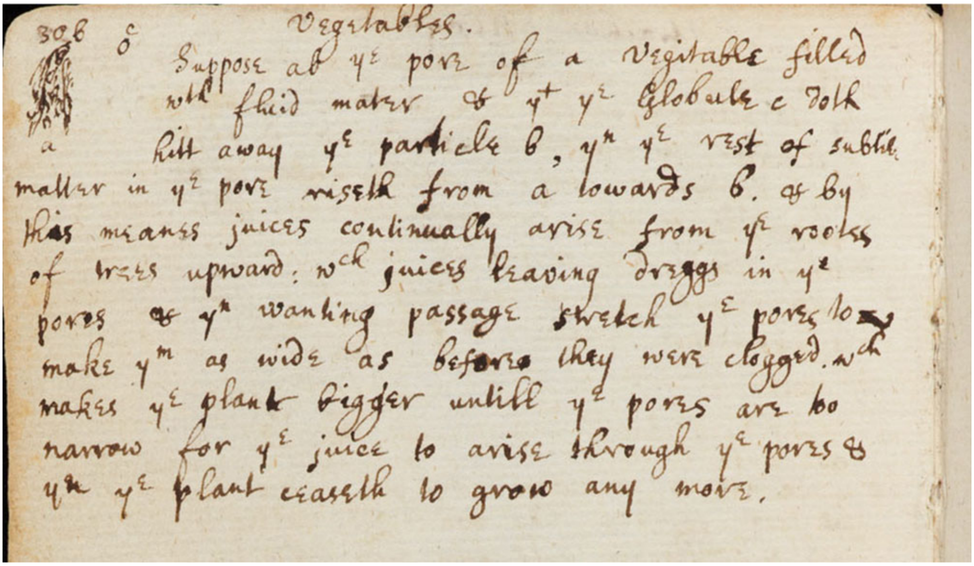
Since the first half of the seventeenth century, British treatises on husbandry and plant cultivation discussed sap moving within plants and trees, generally attributing it to the heat of the Sun making water rise. This claim was widely accepted by scholars of different traditions. In the Aristotelian strand, for instance, the heat of the Sun remained metaphysically necessary to account for the functions of nutrition and growth in plants, while in corpuscularian (and atomistic) explanations of plant life, such as Isaac Beeckman's (1588–1637) and Descartes' mechanistic interpretations, as well as Gassendi and Digby, the Sun played a major role in widening the pores of plants and allowing for the ascent of sap.[13] The difference was that Aristotelian scholars appealed to the vegetative soul as efficient cause, while the latter claimed no soul was the cause of this motion. A similar interpretation appeared in natural philosophers such as Bacon and Sir Hugh Plat, who also appealed to spirits and appetites. In a note jotted down between 1661 and 1665, i.e., before the writing of *De gravitatione* and the *Principia* (1687), and suitably entitled 'Vegetables', Isaac Newton (1642–1726) suggests that light knocks molecules of liquid within the pores of vegetables, making sap rise from the roots of the tree and nurture the plant until the pores are too narrow (see figure 1). Although the context of Newton's notes is unknown, his interpretation is consistent with the claim that a source of heat makes the sap ascend through plants.[14]

Attention to the rise of water in plants also developed from the trials of master gardeners, while a philosophical gardening emerged at the time, as Vera Keller has shown.[15] In 1618, for instance, in *A new orchard and garden, or the best way for planting, grafting, and to make any pound good for a rich orchard …*, William Lawson (*ca* 1554–1635) presented three major claims about sap. The first is a comparison between sap and blood, a common aspect of pre-modern botany. He claimed that 'the sap is the life of the tree, as the bloud is to mans body: neither doth the tree in winter (as is supposed) want his sap, no more than mans body his bloud which in winter, and time of sleep draws inward. […] for the tree at all times, even in winter is nourished with sap'. The second is that sap is what nurtures the plant and makes it grow. For this reason, he claimed: 'the sap never descends, as men suppose, but is consollidated & transubstantiated into the substance of the tree, and passeth (alwayes above the earth) upward […]. 3. I cannot perceive what time they would have the sap to descend. […] 4. The sap in this course hath his profitable and apparent effects, as the growth of the tree […], if the sap descend, it must needs have some effect to shew it.' Connected to this issue, the third claim concerns the motion of sap. Sometimes, this movement 'is forced by the maine streame of the sap, as in top boughs hanging like water in pipes […] under boughs […] can scarcely get sap to live, yea in time dye, because the

13 See Fabrizio Baldassarri, 'Beeckman's corpuscular study of plants', in *Knowledge and culture in the early Dutch Republic: Isaac Beeckman in context* (ed. Klaas Van Berkel, Albert Clement and Arjan van Dixhoorn), pp. 245–263 (Amsterdam University Press, Amsterdam, 2022); and Fabrizio Baldassarri, 'The mechanical life of plants: Descartes on botany', *Br. J. Hist. Sci.* **52** (1), 41–63 (2019).

14 David J. Beerling, 'Newton and the ascent of water in plants', *Nature Plants* **1**, 15005 (2015), online: https://doi.org/10.1038/nplants.2015.5.

15 Vera Keller, 'A "Wild swing to phantsy": the philosophical gardener and emergent experimental philosophy in the seventeenth-century Atlantic world', *Isis* **112** (3), 507–530 (2021). Cf. Rebecca Bushnell, *Green desire: imagining early modern gardens* (Cornell University Press, Ithaca and London, 2003).


308 Vegetables.

Suppose ab ye pore of a Vegitable filled wth fluid mater & yt ye Globule c doth hitt away ye particle b, yn ye rest of subtle matter in ye pore riseth from a towards b. & by this meanes juices continually arise from ye rootes of trees upward: wch juices leaving dreggs in ye pores & yn wanting passage stretch ye pores to make ym as wide as before they were clogged. wch makes ye plant bigger untill ye pores are too narrow for ye juice to arise through ye pores & yn ye plant ceaseth to grow any more.

Figure 1. 'Vegetables', the note by Newton. In Newton's Paper, Trinity College Notebook (MS Add. 3996), fol. 102v. Reproduced by kind permission of the Syndics of Cambridge University Library.

sap doth press so violently upward, and therefore the fairest shootes and fruits are alwayes in the top'. Later, Lawson claimed that 'the Sunne with his heat begins to make the sap stirre more rankely'.[16] Lawson's interpretation is not particularly original, but what is important to note is that he inferred the presence of a source of heat, something that makes the sap rise. This is the Sun.

Lawson's text circulated among naturalists and scholars at the time, as the motion of sap gained momentum in the study of plants. In *Sylva, or a discourse of forest-trees and the propagation of timber* (1664), John Evelyn (1620–1706), a founding Fellow of the Royal Society, referred to Lawson while speaking of sap. As is well-known, this was the first book to bear the Society's *imprimatur*, therefore showing how much the investigation of plants resided at the core of the Society—in fact, Evelyn drew attention to the experiments undertaken by the Society, summarizing Jonathan Goddard's (*ca* 1617–1675) anatomical study of plants, Hooke's microscopical observations and Christopher Merret's (1614/1615–1695) and John Ray's (1627–1705) works.[17] In Evelyn's text, an interconnection surfaces between practical matters (such as ways of improving agriculture) and the need to acquire a sound knowledge of the nature of plants by means of experiments. In his *Elysium Britannicum*, Evelyn suggests the garden as a space for trials and investigations, and envisages a 'gardiner elaboratory', where distillations, extractions and experiments with

16 William Lawson, *A new orchard and garden, or the best way for planting, grafting, and to make any ground good for a rich orchard* (W. Wilson, London, 1648), pp. 24–25.

17 See Thomas Sprat, *The history of the Royal Society of London* (J. Knapton, London, 1734), p. 242: 'of the Pores and Valves in *Wood*: the Anatomy of *Trees*: of the sensitive, and humble *Plant*'. Cf. Lindsay Sharp, 'Timber, science, and economic reform in the seventeenth century,' *Forestry* **58**, 51–86 (1975). Michael Hunter, *Science and society in Restoration England* (Cambridge University Press, Cambridge, 1981).

thermometers were performed.[18] In another part of the manuscript, he discusses the forces to make water rise in pipes as an important knowledge for gardeners to perform delightful experiments with fountains.[19] In the second edition of *Sylva*, Evelyn added that 'the accurate knowledge of the nature of *sap* […] should be observed by some at entire *leisure* to attend it daily',[20] referring to the fact that this observation would provide a clearer knowledge of the nature and variety of trees and plants. But one should also note Evelyn's references to the action of the universal spirit of the world.[21]

The combination between experimentation and a more speculative approach clearly surfaces.[22] In 1658 Ralph Austen (*ca* 1612–1676) published a commentary on Bacon's natural history of plants, and claimed that sap moves only upward and not downward, contrary to Bacon's own claims.[23] A year earlier, he had published *A treatise of fruit-trees* (1657), in which he spelled out six arguments against the downward movement of sap, because 'it is contrary to the law, and course of nature for *sap to descend*: *Natura nil agit frustra*, nature does nothing in vaine'.[24] In this respect, he reduced these arguments to three main reasons. The first is that the downward movement of sap is 'hurtfull, and dangerous',[25] while sap rises 'to make any growth'.[26] Then he discussed the means regulating the ascension of sap, showing how these means work in producing the motion. For instance, the 'vicinity, and nearenesse of the sunne', namely, the Sun is what makes 'the *sap* […] increase by degrees', while, when the Sun is absent, the sap rises less abundantly and trees lose their leaves, 'because *sap riseth not up to them sufficient to feed them any longer*, but only so much to preserve life in the Tree'.[27] Accordingly, the Sun draws sap, and makes it rise throughout the tree.[28]

Later, he specified that the Sun is the '*efficient Cause* of the *rising up of sap*, though also (and principally) the *vegetative spirit* (excited by the sunne) carries it up, and disperseth it to all the parts for nourishment & growth'.[29] This explains why sap rises even when the Sun is clouded or absent. Austen thus presents a more precise elaboration of the case, as he suggests the presence of a spirit in vegetation, which he called the principal cause of the movement of sap, while the Sun—namely, heat—is just the efficient cause that activates the spirit. According to Austen, scholars have generally conceived this spirit as 'the soule of Plants',

18 See John Evelyn, *Elysium Britannicum, or the royal gardens* (ed. John Ingram) (University of Pennsylvania Press, Philadelphia, 2001), p. 251.

19 *Ibid.*, p. 434.

20 John Evelyn, *Sylva, or a discours of forest-trees, and the propagation of timber in his majesties dominions* (John Maryn, London, 1670), p. 74.

21 Evelyn, *op. cit.* (note 18), pp. 38, 78.

22 See Peter Anstey and Alberto Vanzo, *Experimental philosophy and the origins of empiricism* (Cambridge University Press, Cambridge, 2023).

23 Ralph Austen, *Observations upon some part of Sr Francis Bacon Naturall History as it concernes, fruit-trees, fruits, and flowers* (Henry Hall, Oxford, 1658), pp. 8–9: experiment 427, 'there is no such thing in nature as descention of sap in any trees whatsoever. […] for there is no Cause, and therefore no such effect: sap is continually ascending all the yeare […] either for the growth of the tree, or for the conservation of it, in life.' [Italics in the text.]

24 Ralph Austen, *A treatise of fruit-trees, shewing the manner of planting, grafting, pruning and ordering of them in all respects, according to rules of experience* (Henry Hall, Oxford, 1657), p. 101.

25 *Ibid.*, p. 107.

26 *Ibid.*, p. 101.

27 *Ibid.*, p. 102. [Italics in the text.]

28 Austen refers to Francis Bacon's *Natural history* and the *Historia de vita et mortis*. See Oana Matei, 'Appetitive matter and perception in Ralph Austen's projects of natural history of plants', *Early Sci. and Med.* **23** (5–6), 530–549 (2018). On these texts, see Dana Jalobeanu in this special issue.

29 Austen, *op. cit.* (note 24), p. 103. [Italics in the text.]

and, following Bacon, he claimed that this is ‘a compound of *flame*, and *Aire*, is of a *flammeous*, and *aerious nature*’. The spirit is thus the ‘*Vehicle*, or meanes of conveyance of the *sap* unto all the parts of the Tree […] its appetite is *upwards*, because it is a light body, and all light things naturally *ascend upwards*’.[30]

Finally, he affirms that acknowledging the descent or circulation of sap results in ‘assigning wrong Causes to effects’.[31] This is especially clear when cutting off branches or twigs of trees, as the Sun and air draw sap and moisture continually out of them, making sap move from the base to the top of plants. This manifestly occurs ‘*as well in Autumne, and Winter, as in Sommer*, so much as to preserve life in Trees by supplying what is extracted by the *Sunne and Ayre*’.[32] The observation of plants helps prove the correctness of the theory, as it is possible to cut off branches and see the movement of sap, drawn by the Sun and air. Yet, new sap moves to fill the vacuum created by the Sun and air emptying the branches, because the sap must continuously supply nourishment to the plant.

Austen here adds a new significant element. Accordingly, air plays a role in the movement of sap together with the Sun, and this interpretation might have been spurred by the appeal to a vegetative spirit, the formal cause of nutrition. Austen thus combined a physical and experiential study of plants with a more speculative approach. Yet, within the Royal Society, a more widespread investigation of vegetal bodies based on observation significantly gained momentum.[33]

Valves, contrivances and pressure in the study of trees

The ascent of sap continued attracting the attention of scholars, who followed Bacon’s advice that they ‘examine nature herself and the arts upon interrogatories’.[34] In 1660 Robert Sharrock devoted one paragraph to ‘whether thence an argument may be made for the descention of Sap’. Yet, he claimed to ‘have found experience very contradictory to their supposalls’.[35] In the end he appeared content to suggest that ‘the sap is in winter […] on the body of the tree coagulated, or crusted into a new coate, encompassing the whole’.[36] In 1665 a committee was appointed at the Royal Society to develop observations on vegetation, and on 19 April of the same year Daniel Coxe (*ca* 1640–1730) compiled a list of ‘inquiries concerning vegetation’, namely, 78 queries with diverse aims,[37] making clear, however, the important attention to be devoted to the circulation or motion of sap.[38] In 1668 the

30 *Ibid.*, p. 104. [Italics in the text.]

31 *Ibid.*, p. 107.

32 *Ibid.*, p. 107. [Italics in the text.]

33 T. Sprat, *The history of the Royal Society of London* (Martyn, London, 1667), pp. 61–76. P. Anker, ‘The economy of nature in the botany of Nehemiah Grew (1614–1712)’, *Archs Nat. Hist.* **31** (2), 191–207 (2004), p. 196.

34 Francis Bacon, *Works of Francis Bacon* (ed. J. Spedding, R. L. Ellis, and D. Denon Heath), vol. IV, p. 261 (Frommann, Stuttgart, 1962).

35 Robert Sharrock, *The history of the propagation & improvement of vegetables by the concurrence of art and nature* (A. Lichfield, Oxford, 1660), p. 60.

36 *Ibid.*, p. 60.

37 Thomas Birch, *History of the Royal Society*, 4 vols (London, 1756), vol. 2, pp. 29 and 32–40. On the interest in plants in Boyle and Coxe, see Antonio Clericuzio, ‘Plant and soil chemistry in seventeenth-century England: Worsley, Boyle and Coxe’, *Early Sci. Med.* **23** (5–6), 550–583 (2018).

38 See, for instance, ‘An experiment on aloe Americana Serrati-folia weighed; seeming to import a circulation of the sappe in plants, by the same Dr. Merret’, *Phil. Trans.* **2**, 455–457 (1667). Cf. H. H. Thomas, ‘Presidential address: experimental plant biology in pre-Linnean times’, *Bull. Br. Soc. Hist. Sci.* **12** (2), 15–22 (1955), at p. 18.

committee produced a deliberation on a list of experiments inviting scholars to perform further observations on the juices of trees, namely, 'to recommend the enlargement of the said knowledge, by further Experiments, to all Ingenious and Industrious Men'.[39] This list includes a series of 20 queries '*Concerning Vegetation, especially the* Motion *of the* Juyces *of Vegetables, communicated by some Curious persons*',[40] with the final remark that, in raising these queries, the aim was to invite inquisitive people to perform and share their observations '*for further elucidation of the yet too obscure nature of* Vegetation'.[41]

In 1668 and 1669 several articles of the *Philosophical Transactions* focused on this issue.[42] For example, Martin Lister (1639–1712), Francis Willughby (or Willoughby, 1635–1672) and John Ray performed several trials on bleeding sycamore trees, therefore exploring the motions of sap at various stages of the life of plants. In this sense, as Anna Marie Roos has noted, it was not surprising that in 1670 Henry Oldenburg remarked to Lister that the Fellows of the Royal Society 'were copious at the time in discoursing upon the motion of Sap in Trees'.[43]

A more interesting note surfaces towards the end of the 1660s when, in replying to Hooke, Boyle claimed it possible that 'Nature […] may have made such Contrivances in Plants, as to make Liquors ascend in them to the Tops of the tallest Trees',[44] which he considered equivalent to valves. At this stage, Boyle suggests that there are valves in plants easing the motion of sap, but it is not clear if he actually performed this experiment or observed plants. It is more likely that he was merely extending his physical explanation to the case of plants. In the review of Boyle's *New experiment*, a text entirely devoted to experimentation concerning the rise of water, 'touching the spring and weight of the air', that is, the movement and rise of liquids in pipes, the author emphasizes Boyle's attention to pressure, gravity and height, which characterizes the attention to static principles north of the Alps,[45] notions he applied to plants too, although we do not know how much he observed vegetal bodies.[46]

Similarly, Christopher Wren (1632–1723) was working on the rise of sap in trees, inquiring: 'by what mechanisme is water raised to such a height, as in Palmitos to 120 foot high? A skillfull Engineer cannot effect this without great force and a complicated engine, which Nature doth without sensible motion […] the reason of this is obscure as yet to naturalists.'[47] This passage is meaningful: Wren suggests an imbalance between the

39 'A suggestion for taking more notice, than hath been done formerly, of the juyces of trees, by tapping them', *Phil. Trans.* **3**, 801–802 (1668).

40 'Queries concerning vegetation, especially the motion of the juyces of vegetables, communicated by some curious persons', *Phil. Trans.* **3**, 797–801 (1668).

41 *Ibid.*, p. 799.

42 See, for instance, John Beale, 'Some communications, relating to the queries about vegetation, publish'd in Numb. 40 of these tracts', *Phil. Trans.* **3**, 853–862 (1668), at p. 854. See also 'Answers to some of the queries, which were recommended by Sir. R. Moray to Sir Phil. Vernatti …', *Phil. Trans.* **3**, 863 (1668); 'Additional answers of Dr. Tonge to some of the queries about vegetables', *Phil. Trans.* **3**, 880–881 (1668).

43 Oldenburg to Lister, 11 February 1670, *The correspondence of Henry Oldenburg* (ed. A. Rupert Hall and Marie Boas Hall), vol. 7, p. 452 (University of Wisconsin Press, Madison, 1965–1986).

44 Robert Boyle, 'A continuation of new experiments physico-mechanical touching the spring and weight of the air, and their effects', in *The works of Robert Boyle* (ed. Michael Hunter and Edward B. Davis), 14 vols, vol. 6, pp. 106–108 (Pickering & Chatto, London, 1999).

45 On the characterization of the study of liquids north of Italy, see Bertoloni Meli, *op. cit.* (note 4) pp. 166–189. See also Cesare S. Maffioli, *Out of Galileo: the science of waters, 1628–1718* (Erasmus, Rotterdam, 1994).

46 See 'An account of two books. A Continuation of New Experiments Physico-Mechanical, touching the Spring and Weight of the Air, and their Effects; the 1. Part, & by the Honourable Roberto Boyle …', *Phil. Trans.* **3**, 845–852 (1668), esp. p. 848.

47 Lucy Phillimore (ed.), *Sir Christopher Wren: his family and his times, with original letters and a discourse on architecture … 1585–1723* (Kegan, Trech & Co, London, 1881), p. 298.

natural phenomenon in vegetables and the attempts to replicate it by engineers, thus highlighting a distance between these two cases—differently from Digby's parallel seen earlier—as the mechanism to raise water remains complicated to perform by an engineer and cannot be easily reproduced in a laboratory. But he tried to solve this question by means of his experimental investigations, as he performed an observation using an apparatus composed of a glass pipe filled with water, with valves and smaller pipes (see figure 2), according to which 'the water is sucked up to supply it and opens constantly from valve to valve, let the height be what it will […] This is what such an Engine will performe; it remains we should shew that the fabrick of Trees is naturally such a kind of pneumaticall Engine'.[48] Accordingly, whether the ascent of sap in plants corresponds to the movement of water in glass pipes should be demonstrated and observed, and a correspondence between nature and engine would ultimately result.

In those years, John Beale (ca 1608–1683) suggested a cursory comparison between the internal parts of plants and its channels as 'the *natural Limbecs*, where the common Raine, Water, and Air, are digested into very much differing Leaves, Fruit, Seed, Resins, Gums, etc'.[49] While gaining momentum as suitable objects—comparable to alembics or pipes—for several observations and experimentation, plants thus seem to correspond to artificial and laboratorial instruments. Although fermentation remains a central issue to the question, both pressure and the presence of contrivances shift the focus of the study of the ascent of sap in plants toward the physical investigation of the motion of liquids.

Nehemiah Grew: plants as laboratories of physics and botany

In the dedicatory letter of the *Anatomy of plants* (1682), Nehemiah Grew proclaims the aim to explain 'the Ascent of the Sap, the Distribution of the Aer, the Confection of several sorts of Liquors, as Lympha's, Milks, Oyls, Balsames; with other parts of Vegetation [which] are all contrived and brought about in a Mechanical way'.[50] Grew's mechanical framework in explaining the movement of sap cannot be overstated. This is especially expounded in paragraphs 21, 22 and 24–28 of Chapter 3, 'Of the trunk', in Book 1, and later in Book 3.

In the earlier chapters, the movement of sap arises as he discusses plant nutrition—for instance, he claims that 'the *Sap* prepared in the *Cortical Body*, is as the *Bloud* [of animals], and that the part thereof prepared by the *Lignous*, is as the *Nervous Spirit*'.[51] And later he describes the fermentation of sap as the 'first *Vegetations*',[52] that is, a way of performing nutrition in the roots and in the trunk. At this stage, fermentation and sap appear connected, at least insofar as sap is concocted and transformed within plants and nurtures the body. In paragraph 30 of Chapter 2, Grew affirms that sap has 'a Double, and so a *Circular* Motion, in the *Root* […] which is Descent', and 'a Motion proper to it […] to feed the *Trunk*: for which, the Sap must also […] have a more especial Motion of

48 Christopher Wren, *Parentalia: or, memoirs of the family of the Wrens* (Osborn, London, 1750), between p. 242 and p. 243.

49 John Beale, 'The causes of mineral springs further inquired: and the strange and secret changes of liquors examined', *Phil. Trans.* **4**, 1131–1134 (1669), at p. 1133. Cf. Mayling Stubbs, 'John Beale, philosophical garderner of Herefordshire, part 1', *Ann. Sci.* **39**, 463–489 (1982); Dana Jalobeanu and Oana Matei, 'Treating plants as laboratories: a chemical natural history of vegetation in 17th-century England', *Centaurus* **62** (3), 542–561 (2020).

50 Nehemiah Grew, *The Anatomy of Plants* (Walter Rawlins, London, 1682), p. 11.

51 *Ibid.*, chap. 2, § 23, p. 15.

52 *Ibid.*, § 27, p. 16.

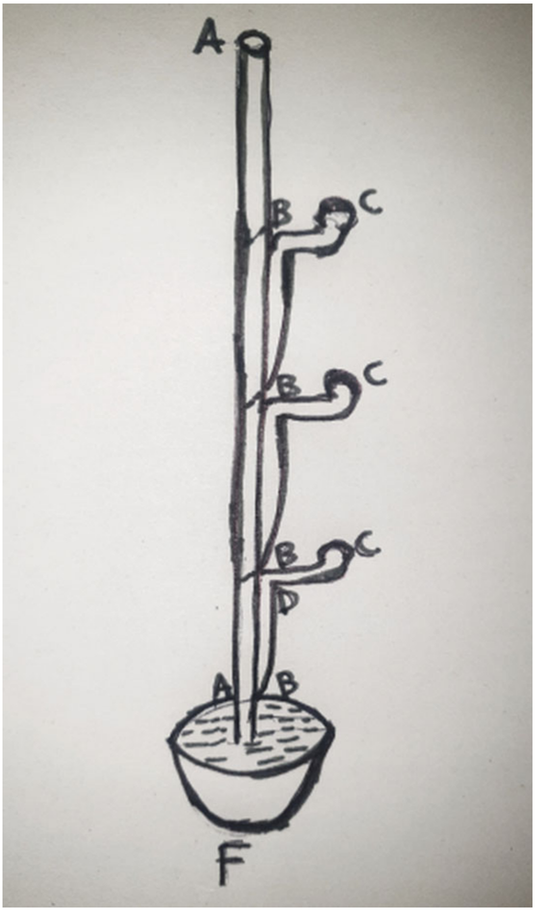


Figure 2. Apparatus used by Christopher Wren to show the ascent of water in trees. (Author's drawing from Wren's *Parentalia*, contained between pp. 242 and 243.)

Ascent'.[53] In paragraph 31 he provides a larger description of the movement of sap in the bark through 'the *Insertions*' of plants, as he ultimately claims that the motion of sap is eased by the structure of the body.

Later, in paragraph 21 of Chapter 3, Grew accounts for plant growth and describes the ascent of sap in more detail. First of all, he repeats that, in the roots, sap is prepared by means of filtrations and fermentations (and by circular motions, too). The more sap is pure and volatile, the more it is 'apt to ascend', as it follows 'its own *magnetical* tendency to *ascend*'.[54] But instead of discussing the ascent of sap from a magnetic perspective, he follows a different line. He affirms that 'by the force and pressure of the *Sap* in its collateral motion, the *Lignous Body* will now more freely and farther be dilated',[55] and the

53 *Ibid.*, § 30, p. 17.
54 *Ibid.*, chap. 3, § 21, p. 22.
55 *Ibid.*, § 22, p. 22.

more the '*Cortical Body*' is dilated, the more the pith and its pores will enlarge. As the trunk grows wider, the consequence of this dilatation is: 'the *Strength* of the *Trunk*, the *Security* and *Plenty* of the *Sap*, its *Fermentation* will be quicker, its *Distribution* more effectual, and its *Advancement* more sufficient.'[56] As a result, sap moves as it dilates the pores of the pith. In this sense, Grew claims the ascent of sap relies on force and pressure, reducing fermentation to a mere activity of transformation of sap during concoction or nutrition. In contrast, it is the force of the sap itself that works in dilating the body of plants.

Some paragraphs later, Grew explores the issue of the security and plenty of sap in plants, ultimately rejecting the role of the Sun as a force that favours the ascent and movement of sap. He claims that, if 'the greater part of the *Sap* would […] be more immediately exposed to the *Sun* and *Aer* [it would] continually be preyed upon, and as fast as supplied to the *Trunk*, be exhausted'.[57] Accordingly, if nothing opposes the attraction of the Sun, all the sap would exit the plants, drying them out. As a result, the attraction of the Sun fails to provide a correct movement of sap, but only extracts it from plants. In contrast, safely protected by the bark and wood, the sap 'will very securely and copiously be conveyed to all the Collateral Parts, and […] the top of the *Trunk*'.[58] As he rejects the claim that the Sun causes the rise of sap in plants, Grew proposes an alternative explanation, which he derives from an investigation of the structure of plants.

In paragraph 31, Grew explains that there is something in the pith that eases the movement of sap, namely, pores, vessels and bladders. He puts forth a couple of experiments to confirm his claim. In the first, he plunges a piece of a plant in some tinted liquors and observes the ascent of this liquor.[59] Yet, the result is unexpected: as Grew stresses, 'it [does] not penetrate the *Pores*, so as to ascend through the Body of the *Pith*'.[60] In his observation, the liquor does not fill the pith entirely, revealing a difference with sap. The reason for this difference resides in the presence of air in the pith used in Grew's experiment, which is absent in living plants. Accordingly, 'the *Pith* in a Vegetating *Plant*, as its Parts or *Bladders* are still generated, they are at the same time also filled with *Sap*; which, as it is gradually spent, is still repaired by more succeeding, and so the *Aer* still kept out'.[61]

The second case is that of cotton. In paragraph 32, Grew stresses that the sap ascends through the ligneous body and through the pith similarly to cotton imbibed in liquor. Since the pith is 'a porous and spongy Body, and in its Vegetative state, its *Pores* or *Bladders* being also permeable, as a curious *Filtre* of *Natures* own contrivance, it thus advanceth, or as people use to say, sucks up the *Sap*'.[62] Accordingly, the sap 'partly ascendeth by the *Pith*, it is likewise in part pressed into the *Lignous Body* or into its *Pores*'. This entails that, when the perpendicular motion is slower, the pressure of the pith pushes the sap to the top of plants—'the collateral motion of the *Sap* […] will be equally strong with the perpendicular at another part, though somewhat beneath it […] and consequently where the perpendicular tendency of the *Sap* hath its term, the collateral tendency thereof, and so

56 *Ibid.*, § 23, p. 23.

57 *Ibid.*, § 26, p. 24.

58 *Ibid*.

59 This was a very common experiment. See, for instance, Henry Power, *Experimental philosophy, in three books containing new experiments microscopical, mercurial, magnetical: with some deductions, and probable hypotheses, raised from them, in avouchment and illustration of the now famous atomical hypothesis* (Roycroft, London, 1664), chap. XII, p. 143.

60 Grew, *The Anatomy of Plants*, *op. cit.* (n. 50), chap. 3, § 31, p. 25.

61 *Ibid*.

62 *Ibid.*, § 32, p. 26.

its pressure into the *Pores* or *Vessels* of the *Lignous Body*, will still continue'. As one may observe in very small glass pipes or in other experiments with two halves of a stick,[63] the sap is raised 'by a pressure, from these into the *Pith*, and from the *Pith* into these [*Vessels*], reciprocally carried on; a most ready and copious ascent of the *Sap* will be continued, from the bottom to the top, though of the highest *Tree*'.[64]

In sum, Grew attributes the cause of the ascent of sap to the pressure of the parts of plants, therefore restricting this activity to the structure of plants. As they are filled with sap, the vessels and the pith dilate themselves, producing a pressure that makes the sap ascend. This explanation appears consistent with the interpretation of the behaviour of water and fluids on the basis of static principles, having recourse to the notion of pressure. And Grew refers to observations performed in pipes and sticks, such as those suggested by Hooke and Boyle. The Sun and air play no role in this activity.

Later in the text, Grew returns to the movement of sap. In Book 3, he claims: 'the Cause also, why the *Vessels* of almost all *Plants*, upon cutting, do yield *Sap*, or *Bleed*; is the *Pressure* which the *Parenchyma* makes upon them. For the *Pith* and other *Parenchymous Parts* of a *Plant*, upon the reception of *Liquor*, have always a *conatus* to *dilate* themselves.' In fact, 'the *Parenchyma* being filled and swelled with *sap*, hath thereby a continual *Conatus* to *dilate* it self; and in the same degree, to press together or contract the *Vessels* which it surrondeth'.[65] As a matter of fact, the movement of sap relies on the pressure the parts of plants exert on the vessels—here, he calls it a conatus. This is something one could observe as plants are cut and yield sap, or bleed, and since they bleed from both ends, this shows that there are no valves in the vessels, as some fellows—namely, Boyle and Wren—of the Royal Society had surmised.

In the following paragraphs, Grew stresses that sap does not ascend 'by virtue of any one *Part* of a *Plant*, alone; that is neither by virtue of the *Parenchyma*, nor by virtue of the *Vessels*, alone. Not by the *Parenchyma* alone. […] Nor by the *Vessels* alone'.[66] According to Grew, if the cause of the ascent of sap resided in the pressure of one part, it would behave exactly like water ascending in glass pipes, where 'there is a certain *period*, according to the *bore* of the *Pipe*, beyond which it will not rise'.[67] Grew repeats the observation performed at the time on the ascent of water in glass pipes, and stresses that something similar occurs in plants. However, similarities stop at a certain point, as Grew recognizes. As previously seen, in this case the ascent of water could reach a certain point, for the pressure of the air prevents water from reaching the top of the pipes, while sap in plants behaves differently. In order to understand the ascent of sap in plants, he suggests performing a different observation. One should 'joyn the *Vessels* and the *Parenchyma* both together in this service'.[68] Grew appeals to a combination of factors, showing that a plant is a system of different parts, and, while it follows the laws of physics, the plant presents a combination of different factors. He thus explains this ascent in paragraph 15, aided by two illustrations from tabula 39 (see figures 3 and 4).

63 On the comparison between pores in plants and pipes, see *Ibid.*, tabula 19, fig. 1.

64 *Ibid.*, chap. 3, § 32, p. 26.

65 *Ibid.*, Book 3, chap. I, § 11, p. 125. Cf. Brian Garrett, 'Vitalism and teleology in the natural philosophy of Nehemiah Grew (1641–1712)', *Br. J. Hist. Sci.* **36** (1), 63–81 (2003), esp. p. 72.

66 Grew, *op. cit.* (note 50), Book 3, chap. I, § 13–14, p. 126.

67 *Ibid.*, § 14, p. 126.

68 *Ibid*.

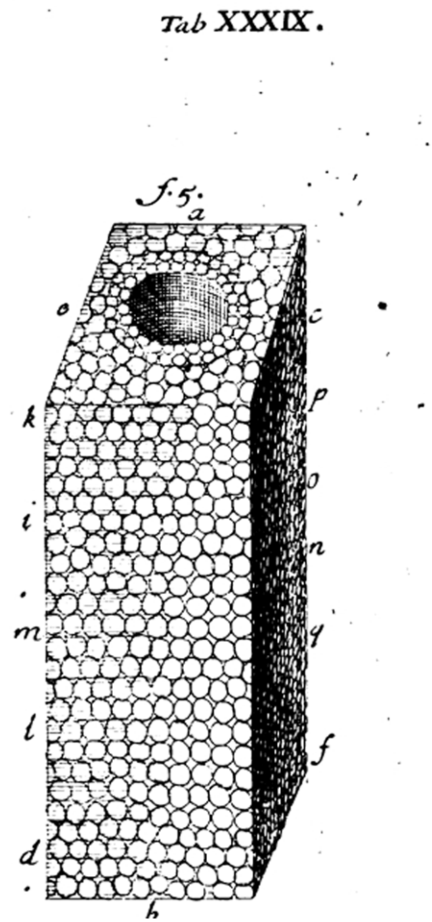


Figure 3. The vessel AB of a plant. From Grew, *op. cit.* (note 50), tabula 39, fig. 5.

According to Grew, the sap in AB would rise for a few inches, from D to L, similarly to what any liquid would do in a glass pipe. In this sense, their ascent follows the static principles and the rule of pressure of the motion of liquids. Yet, in the case of plants there is something more. Indeed, since the bladders of the parenchyma, namely, parts C, E, D and F, 'which surround [the vessel], being swelled up and turgid with *Sap*, do hereby press upon it; and so not only a little contract its bore, but also transfuse or strain some *Portion* of their *Sap* thereinto: by both which means, the *Sap* will be forced to rise higher therein. And the said *Pipe* or *vessel* being all along surrounded by the like *Bladders*; the *Sap* therein, is still forced higher and higher.' In sum: 'the supply and pressure of the *Cisterns* or *Bladders* F D, the *Sap* riseth to L; by the *Bladders* Q L, it rises to M […] and so to the top of the *Tree*.'[69] As the sap ascends, the parts of plants operate a pressure on the vessel, making it continue rising.

69 *Ibid.*, § 15, p. 126.

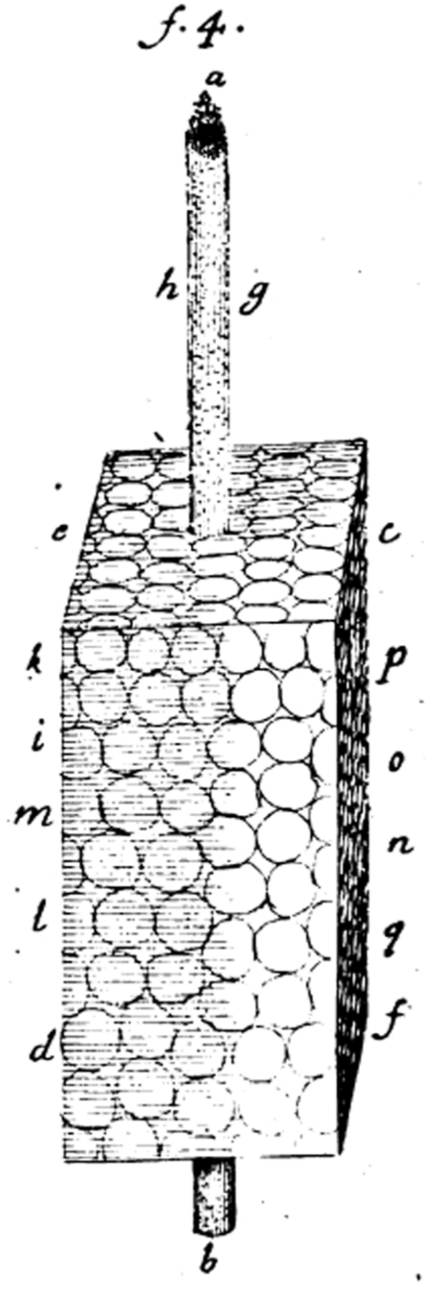


Figure 4. The vessel AB of a plant. From Grew, *op. cit.* (note 50), tabula 39, fig. 4.

In his text, Grew deals with several aspects of the ascent in plants, namely, the role of the Sun, fermentation and the presence of valves, which he rejects altogether. In contrast, he claims that the motion of sap follows the principles of static, as do all liquids, as pressure from the parenchyma eases the ascent of sap. Finally, Grew's investigation entails that the plant should be studied as a whole, and not as a mere sum of different parts.

Marcello Malpighi: mechanics and plants

Let us now focus on Malpighi, who provided a highly mechanical explanation of plant anatomy and physiology. As if he had plants on his dissecting table, he aimed to uncover the mechanical microstructure of their parts and the processes of nature as he did for animals. Malpighi applied a ligature to a tree trunk, revealing that in the outer layers sap flows downwards, and that some plants grow even when planted upside down, showing that there are no valves. He also studied the role of leaves in the preparation of sap. In the *Anatome plantarum idea*, which he sent to Henry Oldenburg in 1672, Malpighi claimed that, when cut and left dangling, branches show a peristaltic motion—which he affirmed as being responsible for the motion of the *mimosa pudica*.[70] Although he discussed this issue again only in the study of insects,[71] it is important to note that, differently from Grew,[72] Malpighi's interpretation of the motion of liquids does not belong to statics or capillarity, or, at least, not entirely, but applied the models of mechanics to living nature.

Malpighi attributed the ascent of liquids through the plants to a range of factors. In Book 1 on the bark, he describes the connection of diverse fibres and vessels, and the utricles within them, where he claims that the sap rises through the anastomoses of vessels and the expansion and contraction due to the heat and cold of air, as these favour the motion of liquids. The text is meaningful:

> As the water enters, it raises upwards […]. But this ascent is not only due to the inner roughness of the pipes [*fistularum*], but also the changes in air temperature (hot and cold, from day and night […]), and its elastic motion, which presses [*urgens*] the outer case of plants [namely, the bark] and promotes and eases the [rising] motion of liquids in the upper direction […], whose demonstration I leave to the Mechanicians.[73]

Later on this page he compares the ascent of sap to the motion of chyle. Although he does not significantly return to this issue, a few pages later he suggests that the ascent of sap differs from circulation, for the sap does not return to a specific place.[74] It is important to note that here Malpighi does not refer to fermentation, but to a variation of temperature, and especially to an elastic motion and pressure exerted by the parts. Accordingly, these are

70 See Marcello Malpighi, *Anatome plantarum idea*, in *Anatome plantarum*, 2 vols (Johannes Martyn, London, 1675–1679), vol. 1, pp. 3–4. Cf. Bertoloni Meli, *op. cit.* (note 7), pp. 240–241.

71 Malpighi compared the disposition of vessels in plants to the trachea of the silkworm. See Bertoloni Meli, *op. cit.* (note 7), pp. 242–243.

72 The peristaltic motion of plants shows another difference between Malpighi and Grew, who rejected it; see Thomas Birch, *The history of the Royal Society of London for improving of natural knowledge*, 4 vols (A. Millar, London, 1756–1757), 3.56. Anna Marie Roos, *Web of nature: Martin Lister (1639–1712), the first arachnologist* (Brill, Leiden and Boston, 2011), pp. 163–164.

73 Malpighi, *op. cit.* (note 70), I:1.5: 'Subintrans itaque humor sursum ascendit, & quasi suspenditur; singula namque portio, quae invicem fibrarum frustule unit, cum parum interius emineat, valvulae vices supplet, & ita minima quaelibet guttula veluti per funem, seu per gradus, ad ingens deducitur fastigium. Hunc autem ascensum non tantum fistularum interior asperitas juvat, sed & successiva aëris temperies, (calida sc. & frigida, ex diei noctisque variis crassibus,) eiusque elasticus motus, qui exteriora corticis involucra urgens, contentorum liquorum motum superiora versus promovere & juvare potest; quae singula sagacioribus Mechanicis demonstranda relinquo.'

74 *Ibid.*, I:1.5: 'In hos igitur transversales utriculos ascendes humor, *chyli* instar, exoneratur, ibique longiorem passus moram, antiquiori succo intime commixtus, & fermentatus, in natura alimenti exaltatur.' *Ibid.*, 1.39: '& quasi peculiarem circulationem.'

the causes of the rise of sap. Although elsewhere in the *Anatome* he embraces the idea of fermentation in plants—as part of the concoction and preparation of nutrients and vegetable matter—he does not consider fermentation as causing the rise of sap. This is not a secondary aspect, especially when related to the last line of the quotation, where Malpighi leaves the explanation of this phenomenon to his fellow mechanicians. Here, he is likely referring to Italian physicists who have explored this issue, without appealing to fermentation.

Domenico Bertoloni Meli has appropriately remarked that Malpighi 'did not refer to the experiments performed at the Cimento Academy in Florence and the Traccia Academy in Bologna on the rise of water in very narrow tubes'.[75] In the text, Malpighi did not engage with these experiments. However, in mentioning such mechanic scholars, he certainly had someone in mind, and it is likely that these are Giovanni Alfonso Borelli and the fellows at the Traccia Academy.

In 1667, for instance, the Modenese astronomer, mathematician and lens-maker Geminiano Montanari (1633–1687), who was professor of mathematics at the University of Bologna and a friend of Malpighi, published *Pensieri fisico-matematici intorno diverse effetti de' liquidi in cannuccie di vetro e altri vasi* (1667 [Physical-mathematical thoughts concerning the diverse effects of liquids in glass-straws and other vases]) on the experiments performed at the Accademia della Traccia.[76] Although he promoted a corpuscular explanation of the capillary, Montanari placed emphasis on the role of pressure and reported an experiment on the ascent of water in the pores of plants, namely, experiment 21 (see figure 5).

This is the text:

> 21. We tried several pieces of wood, of which, when putting a piece cut—as it is said—by the head [*per testa*] on a wet surface, we see appear suddenly drops of water in diverse places of their upper part, [water] risen through the pores of wood, as it does in straws, and it quickly moistens the whole piece of wood both inside and outside (Fig. IV).[77]

In this text, Montanari describes an observation with a piece of wood, whose pores let water enter and rise from the bottom to the top. Accordingly, this occurs because of capillarity. Later in the text, he describes this ascent in living plants, and affirms that through the uses of microscopes one observes the small channels in plants in which sap rises and nurtures the plant.[78] Accordingly, the cause of both ascents is the same capillary. Yet, Montanari adds something more, as he claims that the reader should not be astonished by the fact that sap rises very high in trees, for 'in the pores of plants there is no communication with external air, which presses and counterweights the force that makes humour rising',[79] as there is no limitation to the height plants may reach. While this explanation of plants is rather

75 Bertoloni Meli, *op. cit.* (note 7), p. 248.

76 See Marta Cavazza, *Settecento inquieto. Alle origini dell'Istituto delle Scienze di Bologna* (Il mulino, Bologna, 1990).

77 Geminiano Montanari, *Pensieri fisico-matematici sopra alcune esperienze fatte in Bologna nell'Accademia Filosofica eretta dall'Ill.mo e R.mo Sig. Abbate Carlo Antonio Sampieri intorno diversi effetti de' liquidi in cannuccie di vetro* (Manolessi, Bologna, 1667), p. 11. [Translation is mine.]

78 *Ibid.*, p.49: 'come ingegnosamente provide la Natura alle Piante, & all'Erbe [...] o siano picciolissimi cannaletti, che in qualunque legname così ordinatamente disposti s'offeruano col Microscopio, e che dale radici fino alle sommità delle piante così ben dispensati si stendono, ne' quali, a guise di tanti cannellini ascende l'umor, che nutre la pianta; poiché non ha dubbio alcuno, che la forza con che tant'alto ascende questo humore non sia della medesima cagione originate, della quale ne scorgiamo in questi cannellini gli effetti, si come in fatti vediamo salire l'acqua così manifestamente per li pori del legname.'

79 *Ibid.*, p. 49: 'ne' pori delle piante non habbiamo dalla parte superiore la communicatione dell'aria esterna, che premendoci contrapesi alla forza, con che ascende l'humore, come ne' nostri cannellini [...]' [Translation is mine.]

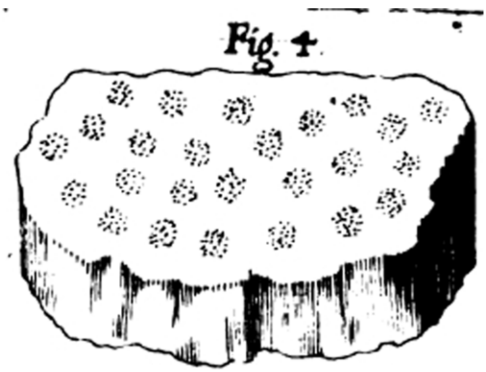


Figure 5. Montanari's representation of water rising in a piece of wood. Montanari, *Pensieri fisico-matematici*, *op. cit.* (note 77), fol. between pp. 16 and 17. Source: https://gallica.bnf.fr.

simplistic, especially when compared to Malpighi's work on leaves and the role of plant transpiration, it reveals the mechanical observations of plants in Bologna, and it is likely Malpighi was aware of this observation.

Another case is in Giovanni Alfonso Borelli (1608–1679), who certainly influenced Malpighi's anatomical studies. In *De motionibus naturalium et gravitate pendentibus* (1670), Borelli devoted several sections to the ascent of water.[80] Differently from his peers, he 'studied primarily flow in closed conduits […] since he conceived his work as a prelude to a treatise on the motion of animals',[81] thus relating his physical investigation to the study of living beings. In *De motu animalium* (posthumously published, 1680–1681), Borelli compared the ascent of water in tubes with the motion of sap in plants. Accordingly, following the case of Santorio Santorio's (1561–1636) thermometer, Borelli conceived the rise of sap in plant vegetation as a combination of rarefaction and condensation occurring in the stem of plants.[82] This explanation does not differ from Malpighi's interpretation of the causes of sap motion.

Borelli affirms that, similarly to a thermometer ABC inserted in a basin DEF, when one heats the flask AB, the rarefaction and condensation of air make water rise to point H or I, the same mechanics operate in the case of plants (see figure 6), as both the rays of the Sun and the air operate in this regard. But Borelli was clear in rejecting any fermentation in plants altogether—and in *De motu animalium* he attacked Malpighi, who had assigned a role to fermentation in vegetal bodies, although, as I have highlighted, Malpighi did not for explaining the rise of sap.[83] In fact, not differently from Borelli, Malpighi recognizes a role for the diverse temperatures of the air in easing the rise of water, but also adds the inner structure of vessels, and a sort of elasticity, without referring to fermentation. Differently from Grew, who discussed the ascent of sap with more attention and likely

80 Giovanni Alfonso Borelli, *De motionibus naturalibus a gravitate pendentibus* (Ferri, Bologna, 1670), pp. 213–244. Cf. Susana Gomez Lopez, 'Marcello Malpighi and atomism', in *Marcello Malpighi: anatomist and physician* (ed. Domenico Bertoloni Meli), pp. 175–189 (Olschki, Florence, 1997).

81 Bertoloni Meli, *op. cit.* (note 4), p. 173.

82 Giovanni Alfonso Borelli, *De motu animalium*, 2 vols (Bernabò, Rome, 1680–1681), Book 2, cap. 13, prop. 175–176, pp. 260–261.

83 See *ibid.*, Book 2, pp. 267–273. Cf. Bertoloni Meli, *op. cit.* (note 7), p. 287.

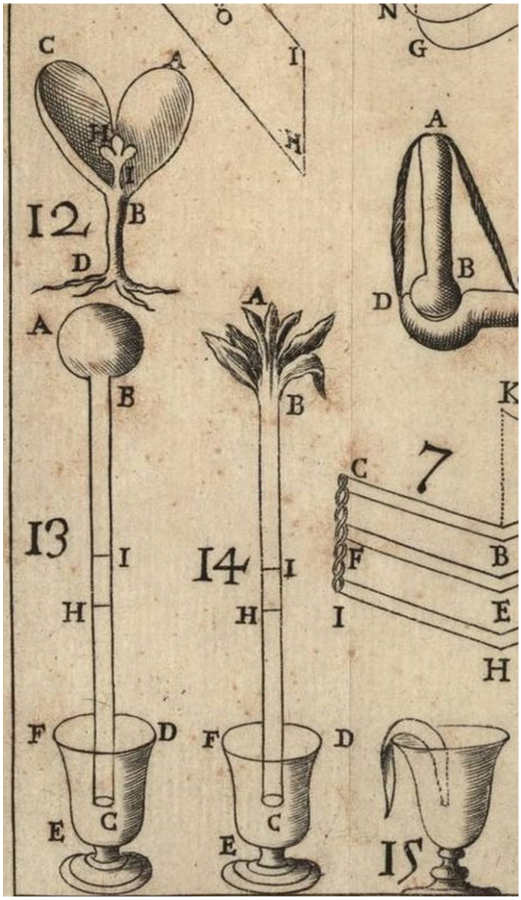


Figure 6. Borelli's analogy between Santorio's thermometer (fig. 13 on the left) and a plant (fig. 14 on the right). Borelli, *De motu animalium*, *op. cit.* (note 82), 2, table 39, figs 13 and 14. Source: https://gallica.bnf.fr.

performed some direct observations of the ascent of water in pipes, Malpighi borrowed the physical explanation for the motion of liquids from his fellow mechanicians, with whom he probably disagreed on several features, but not on this one. Yet, he embedded their mechanical explanation of the rise of sap within a physiological description of plants.

Conclusion: a bigger picture

In the seventeenth century, botany was at the centre of experimental natural philosophy, as plants became an object of laboratorial investigation. Yet, changes emerge, as testified by the studies concerning the ascent of sap. Whereas earlier in the seventeenth century, scholars, gardeners, chemists and natural philosophers attributed the motion of sap to the attraction of the Sun, and specifically to fermentation, as well as to the presence of souls and spirits, later in the century, scholars started following a different path. This concurred with the attenuation of the analogy between the motion of sap and circulation, namely, the animal–plant analogy, as scholars studied plants in their own right. Yet, it took a decisive turn as scholars combined the physical and mathematical investigation of the motion of liquids and ascent of water, namely hydrostatics, with the study of plant physiology in the second half of the seventeenth century. Spurred by Robert Boyle's and Robert Hooke's claim that the same rules of physics should apply both in the case of glass pipes and in the case of plants, in order to confirm this theory scholars were asked to observe plants in physical laboratories. Still, this was not an easy task, making the investigation of the rise of sap in plants a relevant puzzle at the time.

In this article I have explored a few cases of scholars dealing with it from different perspectives. As it surfaces, in the second half of the seventeenth century, scholars placed plants as objects in a physical laboratory, as they appeared analogous to alembics and glass pipes.

A new focus emerged in Nehemiah Grew's and Marcello Malpighi's studies, who devoted their stand-alone works to plants. In this article I have presented their interpretations, and Grew's observations on the ascent of water in glass pipes as well as in plants, claiming that it depends on capillarity, while he acknowledged a difference between these two cases. Grew extended the rules of statics and pressure to the study of the ascent of sap in plants. In contrast, Malpighi leaned toward a mechanistic interpretation, as he was likely informed by the observations performed at the Accademia del Cimento and the Accademia della Traccia, and in particular by Geminiano Montanari and Giovanni Alfonso Borelli, who investigated the physical causes of the motion of liquids in tubes and plants. In sum, the differences between their interpretations follow the divide between the approaches to the mechanical study of liquids, one based on motion and developing in Italy in the Galilean context and the other based on statics and developing north of the Alps.[84]

Notwithstanding the emergence of a clearer understanding of plants not as merely passive, but as active subjects of nature, in which the ascent of sap is an activity caused by the plant itself, questions remain—neither Malpighi nor Grew provided a definitive explanation of the ascent of sap. In 1679 Leibniz wrote to Edme Mariotte that more observations should be performed on the juices in plants and their motion.[85] In 1686, in *Historia plantarum*, John Ray, who had investigated this issue with the Fellows of the Royal Society, provided a summary of both Grew's and Malpighi's interpretations—the former attributing it to the structure of channels, the parenchyma and so on, and the latter to the fibres—but then suggested that an efficient or impulsive cause should be present in plants.[86] It was only later in 1727 that Stephen Hales (1677–1761) published *Vegetable staticks* and demonstrated by means of several observations in laboratories that the principal driving force to the ascent of sap is plant transpiration, providing a more exhaustive interpretation to plant physiology.[87]

84 For an overview of the French context, namely Edme Mariotte and Claude Perrault's experiments with plants, see Alice Stroup, *A company of scientists: botany, patronage, and community at the seventeenth-century Parisian Royal Academy of Sciences* (University of California Press, Berkeley, Los Angeles, Oxford, 1990), pp. 139–142. For the study of the ascent of sap in the eighteenth century, see Sarah Benharrech in this special issue.

85 Leibniz to Mariotte, 30 June 1679, A III/2; G. W. Leibniz, *Sämtliche Schriften und Briefe* (edition of the German Academy of Sciences, Darmstadt/Leipzig/Berlin: 1923–), pp. 773–774.

86 John Ray, *Historia plantarum* (Clarke, London, 1686), vol. 1, p. 32: 'Quaenam autem ascensus hujusce causa efficiens sue impulsive sit, quae succumb sursum adigat & compellat, nos hactenus latet; nec enim in causis assignatis nobisinenpsis satisfecimus.'

87 On this, see Harvey R. Brown, 'The theory of the rise of sap in trees: some historical and conceptual remarks', *Phys. Perspect.* **15**, 320–358 (2013).

Data accessibility

This article has no additional data.

Declaration of AI use

I have not used AI-assisted technologies in creating this article.

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