Friction and Lubrication in Medieval Europe: The Emergence of Olive Oil as a Superior Agent

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Friction and Lubrication in Medieval Europe

The Emergence of Olive Oil as a Superior Agent

*By John Muendel**

WHEN DEALING WITH THE HISTORY of overcoming friction in medieval machines, one cannot help but be struck by the investigations of Leonardo da Vinci. The *Codice Atlantico,* in particular, demonstrates that by measuring friction's force on both horizontal and inclined surfaces, he was able to introduce the concept that the coefficient of friction is the ratio of its force to the weight or load applied ($\mu = F/W$). His quantitative experiments eventually allowed him to conclude that "every frictional body has a resistance of friction equal to one-quarter of its weight," an approximation that is close to modern standards.[1] In order to reduce such resistance, Leonardo went so far as to devise self-oiling systems for lubricating journals, or axle-ends, and a variety of roller-bearing arrangements, one of which had balls enclosed in a cage or retainer that anticipated recent schemes. A two-piece block that would prevent the axle from jumping out of the bearing was provided with metal bushings, or sleeves, made up of three parts copper and

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Shorter versions of this essay were presented at the annual meetings of the Medieval Academy of America and the International Congress on Medieval Studies, held respectively in April and May 1993 at the University of Arizona in Tucson and Western Michigan University in Kalamazoo. The responses from both audiences were very helpful in sharpening my perspective. I am also grateful for the assistance and cordiality of the staffs of the Archivo di Stato of Florence, Interlibrary Loan of the Memorial Library of the University of Wisconsin–Madison, and the Rare Book and Special Collections Library of the University of Illinois at Urbana-Champaign. I was unable to take advantage of *Mulini da grano nel Piemonte medievale: Secole XII–XV,* edited by Rinaldo Comba (Cuneo: Società per gli Studi Storici, Archeologici ed Artistici della Provincia di Cuneo, 1993), before my essay went to press. The contributors' examples of the use of lubricants and antifriction materials are consistent with those found in my discussion of medieval Turin.

[1] Leonardo da Vinci, *Il Codice Atlantico della Biblioteca Ambrosiana di Milano,* ed. Augusto Marinoni, 12 vols. (Florence: Guinti-Barbèra, 1975–1980), Vol. 3, p. 101, Vol. 4, p. 144 (here and elsewhere, translations are mine unless otherwise indicated). Cf. *ibid.,* Vol. 9, p. 47, Vol. 10, pp. 74–75, Vol. 11, pp. 97–100. See also Theodor Beck, *Beiträge zur Geschichte des Machinenbaues* (1899), 2nd ed., enlarged (Berlin: Julius Springer, 1900), p. 97; Igor B. Hart, *The Mechanical Inventions of Leonardo da Vinci* (1925), 2nd ed. (Los Angeles/Berkeley: Univ. California Press, 1963), p. 141; Duncan Dowson, *History of Tribology* (London/New York: Longman, 1979), pp. 99–100; and Kenneth D. Keele, *Leonardo da Vinci's Elements of the Science of Man* (New York: Academic Press, 1983), pp. 123–124.

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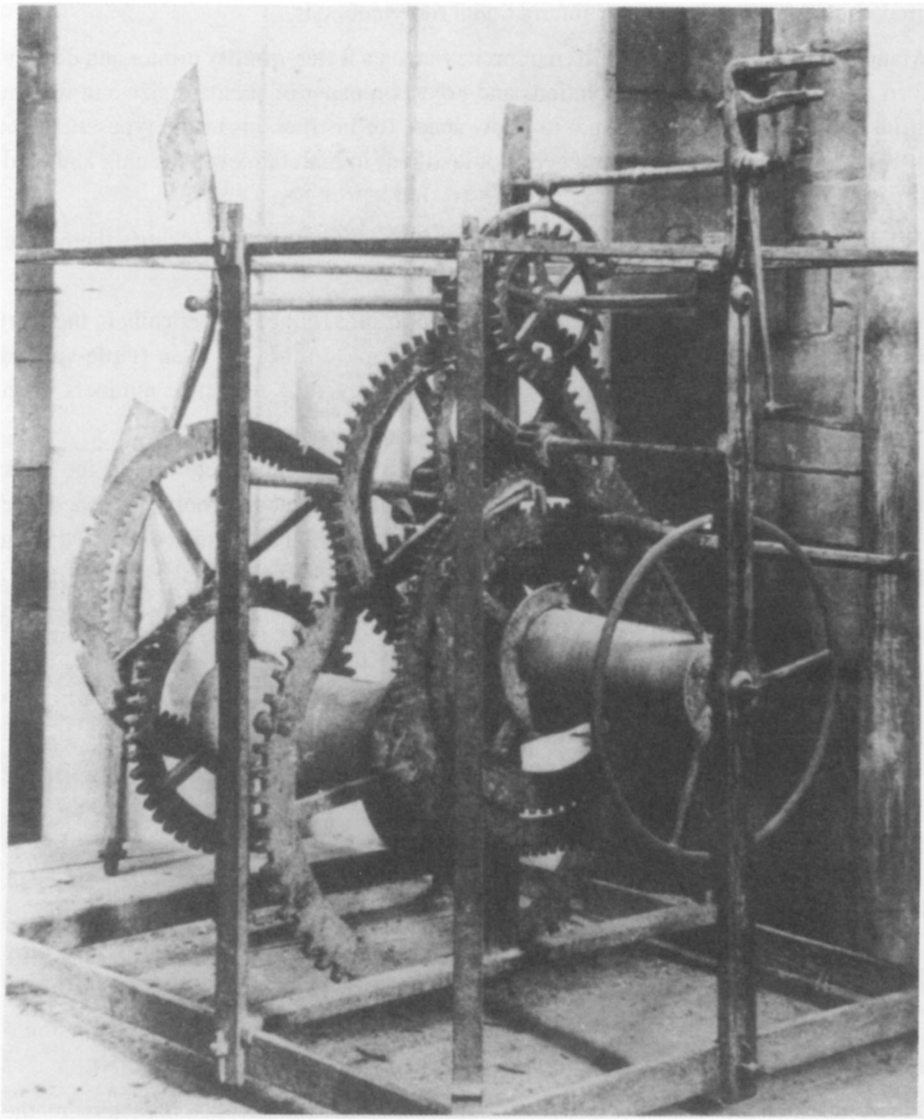

The medieval clock of the Salisbury Cathedral (ca. 1386) as rediscovered in 1929 by T. R. Robinson. Note the brass bushings in the wrought-iron frame to the right. From Duncan Dowson, History of Tribology *(London/New York: Longman, 1979), Figure 6.2.*

seven parts tin. The incorporation of this "mirror metal," as he called it, indicates that Leonardo was also aware of low-friction metallic materials.[2]

It would appear from these few illustrations that Leonardo's mechanisms were far ahead of the contemporary techniques of the late fifteenth and early sixteenth centuries. But however advanced his devices may have been, they do not present a complete picture of the effective remedies employed in his day for reducing friction in machines. His technological intuition allowed him to contrive the most sophisticated solutions to problems regarding this resistance, but it seems that he failed to delve thoroughly into the mundane details concerning lubrication. It is true that what is lacking might be found in his manuscripts that have not as yet been uncovered. After all, since Leonardo was perennially in search of new pigments, varnishes, and gums for his paintings and decorative plates, he was aware of a variety of oils.[3] There are two factors, however, that argue against his thorough understanding of them as lubricants. First, Leonardo had a definite tendency to be sidetracked by problems immediately impinging upon his mind, so that larger projects remained unfinished. Second, his philosophical preoccupations prohibited a deeper examination of the more common techniques of his day. Influenced by the humanistic leanings of Roberto Valturio and Francesco di Giorgio Martini, a large number of his designs are either imaginative projections of antique models or pure mechanical abstractions that ultimately have no direct link to reality. Although he was intensely absorbed in nature and its actions, his vision of a universal science of inner microcosmic laws presupposed a scheme that limited his more scientifically inclined investigations.[4] If Leonardo had found himself totally involved in contemporary techniques, he would have had to adjust his abstract speculations rather thoroughly. Theoretical views predominated in his thinking, and therefore his empirical pursuits were essentially disjointed.

LOW-FRICTION MATERIALS IN A STRINGENT MEDIEVAL ECONOMY

During the Middle Ages the application of pure empirical methods is evident in the actual machines built by people who had no intellectual pretensions to cloud their thinking. Their machinery had to be operated within severe economic constraints, so that any undue expense was eliminated while maximum efficiency was maintained. Thus, in both the city and the countryside of Florence, the metals of worn-out tools were methodically reprocessed to produce new implements and thereby avoid the expense of replacement; if a tool was involved in unusually strenuous activity, only the working edge was reinforced with steel. In the area of the Casentino many inhabitants, whatever their occupations, made themselves familiar with the techniques and machines of others so that they could pay off

[2] Ladislao Reti, "Elements of Machines," in *The Unknown Leonardo,* ed. Reti (New York: McGraw-Hill, 1974), pp. 264–287, on pp. 281, 284–286; and Reti, "The Two Unpublished Manuscripts of Leonardo da Vinci in Madrid," in Reti and Bern Dibner, *Leonardo da Vinci: Technologist* (Norwalk, Conn.: Burndy Library, 1969), pp. 9–33, on pp. 15–23. See also Beck, *Beiträge zur Geschichte des Machinenbaues,* pp. 100–102, 319–325; Dowson, *History of Tribology,* pp. 102, 105–107; and Vernard Foley, Edward R. Blessman, and James D. Bryant, "Leonardo da Vinci und das Fahrrad," *Technikgeschichte,* 1983, *50:*100–128, on pp. 108–123.

[3] Ladislao Reti, "Le arti chimiche di Leonardo da Vinci," *Chimica e l'Industria,* 1952, *34:*655–667, 721–743, on pp. 664, 665–666, 731–733, 734, 736–742. See also Keele, *Leonardo's Elements of the Science of Man* (cit. n. 1), pp. 80–81.

[4] Keele, *Leonardo's Elements of the Science of Man,* p. 23; Martin Kemp, *Leonardo da Vinci: The Marvellous Works of Nature and Man* (Cambridge, Mass.: Harvard Univ. Press, 1981), pp. 99, 180 (unfinished projects), 84, 161, 176–177 (antique models), 114–125 (universal science); Abbot Payson Usher, *A History of Mechanical Inventions* (1929), 2nd ed. (1954; New York: Dover, 1989), p. 271; and Augusto Marinoni, "L'essere del nulla," in *Leonardo da Vinci: Letture vinciane, I–XII (1960–1972),* ed. Paolo Galluzzi (Florence: Giunti-Barbèra, 1974), pp. 7–28, on pp. 27–28 (mechanical abstractions).

debts through work rather than monetary exchange.[5] The iron industry of Othe in southern Champagne produced frying pans, nails, and other accessories without the benefit of waterpower, the usual source of energy for medieval *fabricae.* The workers traveled with their equipment and the disassembled exterior parts of wooden forges to the places where the ores could be found and prepared. The manufacture of the iron parts for a windmill by the local blacksmiths and the reassemblage of twenty crossbows by a glassmaker indicate that the labor-saving diversity of the artisans of Othe was surely equivalent to that of the residents of the Casentino. The economic efficiency of the medieval technological processes these terrestrial endeavors demonstrate can also be seen at sea. It is very likely that the crusading ships of the late eleventh and twelfth centuries were deliberately built to be dismantled at the end of their journeys in order to construct siege towers and heavy artillery. The procedure continued into the thirteenth century: during his conquest of Majorca in 1229–1230, James I of Aragon used counterweight trebuchets, or stone-throwing engines, that were made, as he himself reported, by sailors from Marseilles "after our own fashion, out of the yards and spares of ships."[6]

It is not difficult to surmise, therefore, that a knowledge of materials was essential to any technological pursuit during the Middle Ages and that the application of this knowledge was particularly important to problems of overcoming friction, the bane of any functioning machine. In medieval Denmark stones of granite, flint, and quartzite were inserted into the soles, or undersides, of wooden ploughs to facilitate their movement, while the journals of wheeled ploughs were studded with pebbles in order to overcome attrition. The pivot and bearing of a ninth-century horizontal mill found in the bog of Moycraig in Ireland were made of stone, a material that for centuries thereafter was commonly employed for the pillows of hydraulic machinery. Another ninth-century horizontal mill, located at Tamworth in Staffordshire, England, demonstrates that a bearing could be made of a high-quality steel whose carbon content must have been carefully adjusted to give it a particularly long life.[7] The bearings of these machines, identified by a horizontal waterwheel affixed to the lower end of a vertical shaft that above was attached to the upper millstone, or runner, were continually subjected to the weight of the runner and the turning of the pivot at the end of the shaft. These pillows had to be durable indeed.

To economize, however, medieval artisans of the West frequently used inexpensive, repairable wrought iron as a material for their pivots and bearings, a pairing that produces a coefficient of friction as low as 0.123. Such a combination was found in the horizontal mills of medieval Pistoia, which must stand as an example of these machines that were

[5] John Muendel, "The Mountain Men of the Casentino during the Late Middle Ages," in *Science and Technology in Medieval Society,* ed. Pamela O. Long (New York: New York Academy of Sciences, 1985), pp. 29–70, on pp. 40–43 (steel reinforcement), 38, 47–56; and Muendel, "The Internal Functions of a Fourteenth-Century Florentine Flour Factory," *Technology and Culture,* 1991, *32*:498–520, on p. 510.

[6] Philippe Braunstein, "Les forges champenoises de la comtesse de Flandre (1372–1404)," *Annales: Économies, Sociétés, Civilisation,* 1987, *42*:747–777; R. Rogers, *Latin Siege Warfare in the Twelfth Century* (Oxford: Clarendon, Oxford Univ. Press, 1992), pp. 72, 203–204; and Jim Bradbury, *The Medieval Siege* (Woodbridge, Suffolk: Boydell & Brewer, 1993), p. 266 (quotation).

[7] On the Danish plow see Girth Lerche, "The Ploughs of Medieval Denmark," *Tools and Tillage,* 1970, *1*(3):131–149, on pp. 131–137, 143–146; and Dowson, *History of Tribology* (cit. n. 1), pp. 82–90. On the Moycraig mill see Richard Holt, *The Mills of Medieval England* (Oxford/New York: Blackwell, 1988), p. 128; P. A. Rahtz, "Medieval Milling," in *Medieval Industry,* ed. D. W. Crossley (London: Council for British Archaeology, 1981), pp. 1–15, on p. 6; and Dowson, *History of Tribology,* pp. 234–235. On stone pillows see Robertson Buchanan, *Practical Essays on Mill Work and Other Machinery* (1814), 3rd ed., with additions by George Rennie (London: John Weale, 1841), p. 345; and Holt, *Mills of Medieval England,* pp. 125–126. On the Tamworth mill see Rahtz, "Medieval Milling," pp. 3–6, 13–14; and Holt, *Mills of Medieval England,* pp. 5–7, 127–128. Although he could not take advantage of the new dating for the Tamworth mill, see Dowson, *History of Tribology,* pp. 236–237, for a photograph and sketch of the steel bearing.

then operating throughout Europe.[8] During the second half of the thirteenth century iron discs, or *arrondelles,* apparently acted as overlapping bearings to eliminate friction at the axle-ends of the bell that swung in the cathedral of Freiburg; the same kind of large, thick plates, the forerunners of Leonardo's system, functioned on the main axle of the trebuchets that defended the Burgundian town of Vellexon during the Hundred Years' War, specifically between 1409 and 1410.[9] The second of the so-called anonymous Hussite engineers, who composed his sketchbook between the mid-1480s and the early 1490s, draws a boring device whose iron pivot at the top of the vertical shaft turns in a square mass of iron.[10] A construction crane and a gearing mechanism run by a crank and flywheel incorporate iron pins and pillows. The engineer even goes so far as to conceive of an earth-hauling vehicle and a three-wheeled siege engine with wheels that are rimmed with iron and turn in tracks, or troughs, of the same substance.[11] The use of iron running on iron as an effective remedy against friction is confirmed by Georgius Agricola's detailed analysis of the standard water-raising winches of sixteenth-century Germany. One of the winches he describes has a vertical axle turned by the feet of two men treading on a cleated platform surrounding the lower part of the beam. The upright axle, which communicates power for winding the rope by means of a right-angled gearing system above the workers, has iron journals at its extremities, both rotating in iron bearings (see Figure 1). Two other winches are simple

[8] John Muendel, "The Horizontal Mills of Medieval Pistoia," *Technol. Cult.,* 1974, *15:*194–225, on pp. 194–199. (The *puntaruolo* is the pivot, the *ralla di ferro* the bearing.) George Rennie demonstrated that wrought iron sliding on wrought iron with weights increasing from 14 to 192 pounds produced 0.160 as the highest coefficient of friction, at 36 pounds, and 0.141 as the lowest, at 192 pounds; see George Rennie, "Experiments on the Friction and Abrasion of the Surfaces of Solids," *Philosophical Transactions of the Royal Society of London,* 1829, *119* (Pt. 1): 143–170, on p. 158. In his experiments concerning iron running on iron without lubrication, Arthur Morin, another nineteenth-century specialist in mechanics, achieved a coefficient of friction of 0.123 at 734 pounds of pressure. At about 1,113 pounds of pressure he attained a coefficient of 0.137; see Arthur Morin, *Nouvelles expériences sur le frottement,* 4 dissertations, Diss. 2: *Nouvelles expériences sur le frottement faites à Metz en 1832* (Paris: Bachelier, 1834), p. 68. From these experiments one can see that an increase in pressure does not necessarily increase the resistance of friction. In fact, it commonly reduces it because the surfaces become condensed and therefore less liable to abrasion. Note that to obtain the coefficient in Rennie's calculations, the "weight required to move it" is divided by the "weight to be moved," i.e., *F/W.*

[9] Bernhard Rathgen, *Das Geschütz im Mittelalter* (Berlin: VDI Verlag, 1928), p. 624 n. 35, fig. 4 (Freiburg). On p. 626 he transcribes the original description: "Faire esdiz angins plusieurs grosses et large platennes de fer appellées arondelles mises et assises es pertux des perches et gemelles desdiz angins et es pendans des arches d'iceulx." Cf. Vernard Foley, Darlene Sedlock, Carole Widule, and Dave Ellis, "Besson, Da Vinci, and the Evolution of the Pendulum: Some Findings and Observations," *History and Technology,* 1988, *6:*1–43, on p. 31. The latest scholar to treat Leonardo's arrangement for suspending a bell is Carlo Pedretti, "La campana di Siena," in *Prima di Leonardo: Cultura delle macchine a Siena nel Rinascimento,* ed. Paolo Galluzzi (Milan: Electa, 1991), pp. 121–134, on pp. 126–132.

[10] Anonymous of the Hussite Wars, *The Technological Illustrations of the So-Called "Anonymous of the Hussite Wars": Codex Latinus Monacensis 197, Part 1,* ed. Bert S. Hall (Wiesbaden: Ludwig Reichert, 1979), p. 34 (date of composition). The manuscript of the "Anonymous" was originally thought to have been composed by one author during the Hussite Wars, or around 1430. Hall has shown that the piece was produced by two different engineers much later in the century. The two exemplify the widely traveled technicians of the fifteenth century, who, in most cases, had no formal education. The separate parts of the manuscript were combined by some unknown person around 1500. Thereafter, the text circulated in southern Germany until it came into the hands of the renowned German orientalist and book collector Johann Albrecht von Widmannstetter (1506–1557), after whose death it became part of the Duke of Bavaria's Hofbibliothek, now the Bayerische Staatsbibliothek (pp. 28–42). For the boring device see fol. 36v. In his commentary (p. 187) Hall suggests that the square mass of iron acts as a weight to force the drill down. Since it is mounted on two stationary horizontal beams, this force would not be a factor. It would be better to see the mass as a large iron bearing through which turns an elongated iron pivot.

[11] *Ibid.,* fols. 38r, 47v, and pp. 188, 195 (iron pins and pillows), fols. 35v–36r, 48v, and pp. 185–186, 195 (other devices). For the amount of friction in the bearings and block-and-tackle rigging of sixteenth-century cranes see H. Arthur Klein, "Pieter Bruegel the Elder as a Guide to Sixteenth-Century Technology," *Scientific American,* 1978, *238*(3):134–140, on p. 136. My thanks to Vernard Foley of Purdue University for leading me to this reference.

Figure 1. *A windlass for raising large loads of water from great depths (1556). Note that an iron journal turns in an iron socket set into a block at* B *and into a roof beam at* C. *A cogwheel interacts with a lantern pinion at* G *to form a right-angled gearing system. From Georgius Agricola,* De re metallica, *ed. and trans. Herbert Clark Hoover and Lou Henry Hoover, 2nd ed. (New York: Dover, 1950), p. 163.*

windlasses, essentially differentiated by one's possessing a flywheel. They have iron sleeves in which the horizontal, and presumably iron, axle-ends revolve. The heavy, vertical beam of a fourth winch, a capstan driven by four horses, has an iron pivot turning in a socket of steel, a metal that slightly increases the friction but gives greater durability.[12]

[12] Georgius Agricola, *De re metallica,* ed. and trans. Herbert Clark Hoover and Lou Henry Hoover, 2nd ed. (New York: Dover, 1950), pp. 160–162, 163–166 (the first ed. was published in 1912). Actually, Agricola refers to the iron sockets of only the first windlass; there is nothing regarding the material of the pivots. In the second windlass, which, like the first, is illustrated, it might be difficult to call the left-hand extension of the drum a pivot. See Beck, *Beiträge zur Geschichte des Machinenbaues* (cit. n. 1), p. 130, who states: "Beide Maschinen sind aus Holz konstruit mit Zapfen und Lagerfutten von Eisen"; see also pp. 131–132. Neither Rennie nor Morin does experiments to determine the amount of friction generated by wrought iron sliding on steel. Rennie does show, however, that the lowest coefficient of friction for soft steel running on wrought iron with weights ranging from 14 to 192 pounds was found to be 0.169 at a pressure of 192 pounds; see Rennie, "Experiments on Friction

During the thirteenth and fourteenth centuries the mills of England activated by vertical waterwheels receiving their power either from below or from above their circumferences had wrought-iron bearings known as "pans" or "bowls" (*pannae* or *patellae*), but they acted as cushions for oaken journals at the ends of the horizontal axles. In northwestern France and northern Italy just the opposite was the case: the iron journals of the horizontal axles turned on wood. At Turin the axle-ends, or *pollici,* each weighing as much as twenty pounds, rotated on wooden bearings, or *sollolae,* made from the hard wood of the cornel tree.[13] The fifteenth-century documentation relating to the mills of Milan indicates the use of the same *pollici* (*polices*), but, in the absence of specific bearings, it must be assumed that they revolved on the wheel blocks themselves. This also seems to have been the case for the mills of eastern Normandy, where in the fifteenth century the large horizontal axles of solid oak were capped with iron "butt-ends" without any apparent cushions. At Douai iron fixtures relating to the waterwheel's hub and axle are not specifically identified in the thirteenth-century documentation. As we will see, however, they must have been employed in overcoming friction since lubrication was required.[14] Thus, either the journals or the bearings—or perhaps both—were made of iron.

Such diversity may prompt the question of whether the substances used for pivots and bearings were interchangeable within a specific region. The technological notebooks of Mariano Taccola of Siena and the first of the so-called anonymous Hussite engineers may be of some help in solving this problem, even if the authors' leaps of imagination occasionally lead us astray.[15] Since the works of Taccola, composed between 1419 and approximately 1453, show a clear familiarity with horizontal mills, the machines found in his neighboring territory of Pistoia, the use of iron pins and pillows was very likely.[16]

and Abrasion" (cit. n. 8), p. 157. Morin has steel running on iron, but only with lubricants. He points out that steel sliding on iron with the grains lying parallel to each other causes considerable marring. This occurs under a pressure of approximately 1,106 pounds in all of his experiments with these materials; see Morin, *Expériences,* Diss. 2: *Metz, 1832* (cit. n. 8), pp. 75–76.

[13] Holt, *Mills of Medieval England* (cit. n. 7), p. 125; Rinaldo Comba, "Il principe, la città, i mulini: Finanze pubbliche e macchine idrauliche a Torino nei secoli XIV e XV," in *Acque, ruote e mulini a Torino,* ed. Giuseppe Bracco, 2 vols. (Turin: Archivio Storico della Città di Torino, 1988), Vol. 1, pp. 79–103, on p. 86, table 1; and Annalisa Dal Verme, in Giuliana Alliaud and Dal Verme, "Le spese di gestione e manutenzione dei mulini di Torino nei secoli XIV–XVI," *ibid.,* pp. 148–176, on pp. 149, 152–154, 161.

[14] Luisa Chiappa Mauri, "I mulini ad acqua nel Milanese (secoli X–XV)," *Nuova Rivista Storica,* 1983, *67:*1–59, 259–344, 555–578, on pp. 566–567; Guy Bois, *The Crisis of Feudalism: Economy and Society in Eastern Normandy c. 1300–1550* (New York: Cambridge Univ. Press, 1984), p. 228; and Georges Espinas, *La vie urbaine de Douai au moyen âge,* 4 vols. (Paris: A. Picard, 1913), Vol. 2, p. 416, Vol. 3, p. 416.

[15] For "the need to combine the admiration for classical technical knowledge with the necessity to stimulate the revival of a process of reflection and original experimentation" that leads to many fanciful devices during the fifteenth century see Paolo Galluzzi, "Le macchine senesi: Ricerca antiquaria, spirito di innovazione e cultura del territorio," in *Prima di Leonardo,* ed. Galluzzi (cit. n. 9), pp. 15–44, on pp. 18–19. See also George Basalla, *The Evolution of Technology* (Cambridge: Cambridge Univ. Press, 1988), pp. 64–78.

[16] Mariano Taccola, *De ingeneis: Liber primus leonis, liber secundus draconis, addenda,* ed. and trans. Gustina Scaglia, Frank D. Prager, and Ulrich Montag, 2 vols. (Wiesbaden: Ludwig Reichert, 1984) (hereafter cited as **Taccola, *De ingeneis***), Vol. 1, pp. 35, 36 n. 4, 61, 63, 94, 114, 116 n. 9, 127 n. 1, 133, 144, 148. Cf. Taccola, *Mariano Taccola and His Book "De ingeneis,"* ed. and trans. Prager and Scaglia (Cambridge, Mass.: MIT Press, 1972) (hereafter cited as **Taccola, *Taccola and "De ingeneis"***), pp. 1–21. For entries between 1419 and 1430 see Taccola, *De ingeneis,* Vol. 2, fols. 11v (upper left-hand corner), 59v (upper right-hand corner), 61r (text), 72r. For 1433 see Taccola, *Taccola and "De ingeneis,"* pp. 84, 106–107, 111, 122–123. Because of the small format of these plates see also Mariano di Jacopo detto Il Taccola, *Liber tertius de ingeneis ac edifitiis non usitatis,* ed. J. H. Beck (Milan: Il Polifilo, 1969) (hereafter cited as **Taccola, *Liber tertius de ingeneis***), fols. 7v, 19v, 22r, 30r–v. For the years between 1434/1438 (Scaglia shows that the period could have begun either in 1434 or in 1438) and 1449 see Taccola, *De ingeneis,* Vol. 2, fols. 71v (upper right-hand corner), 83r (left of center), 83v (top), 92r (upper right-hand corner), 97r, 106v (bottom). For 1449 see Taccola, *De machinis: The Engineering Treatise of 1449,* ed. and trans. Scaglia, 2 vols. (Wiesbaden: Ludwig Reichert, 1971) (hereafter

Though he offers no specific descriptions, iron was thus the probable material of the pivots and bearings of the vertical axles in his cranes, capstans, hoists, and grain mills, the latter being run by horses, donkeys, vertical waterwheels, and connecting rods attached to crankshafts. In one capstan, drawn between 1419 and 1427, the cushion for the iron pivot is obviously an elongated piece of that material embedded in an apparently wooden stump. But in another drawing, of a bucket wheel driven by a horse gin (1427–1430), Taccola corrects an error in his depiction and in so doing distinguishes the use of journals on horizontal axles and pointed pivots on vertical shafts, a contrast that, though unintentional, may indicate different antifriction procedures.[17]

In two depictions Taccola demonstrates very clearly that the "hammered" journals of horizontal axles commonly turned on wood.[18] For his mill driven by mercury (1427–1430), cedar, orange, or laurel wood is recommended for bearings that will help resist wear. With regard to his treadwheel drive for raising buckets of water out of a well (1433), oak and ilex, as well as cedar wood, are suggested as sleeves that resist consumption. Perhaps even the apparently iron sockets of his two-piece wheels running on the stubs of fixed wooden axles help to confirm the practice of having iron rotating on wood as a means of reducing friction.[19] But Taccola's specific written information about the pillows of his mercury mill and treadwheel drive should suffice. From these details, we must assume that in all the illustrations in which the iron journals of horizontal axles turn on bearing blocks, those blocks are made of wood, preferably of the kinds specifically recommended by Taccola (see Figure 2).[20] We could say that, conversely, the iron pivots of the vertical shafts rotate

cited as **Taccola, *De machinis***), Vol. 2, fol. 83r (illustration and text). Cf. Taccola, *De rebus militaribus (De machinis, 1449),* ed. and (German) trans. Eberhard Knobloch (Baden-Baden: Koerner, 1984) (hereafter cited as **Taccola, *De rebus militaribus***), pp. 394–395.

[17] Taccola, *De ingeneis,* Vol. 2, fols. 19r, 59r (oriented sideways). The large number of these machines, particularly cranes and capstans, found in the works of Taccola precludes a specific listing of them here. See the editions tabulated in note 16.

[18] The axle of a drive for a bucket chain in Taccola, *Taccola and "De ingeneis,"* pp. 61, 95, and Taccola, *Liber tertius de ingeneis,* fol. 13v, is described respectively as "cum (in) billicis suctilibus" or "cum imbillicis suctilibus" (1433). This apparently common phrase for journals, or axle-ends, is translated literally by Prager and Scaglia as "with thin pivot pins." They suggest that these are thin so that they can be worked by a lathe: "pivot pins thin enough to allow machining by whatever lathe is available" (Taccola, *Taccola and "De ingeneis,"* p. 61). I would claim that they are thin (*subtiles, suctiles* in Latin; *sottili* in Italian) because the worn wrought iron that makes up the journals has been reheated and beaten to give them renewed shape, strength, and smoothness through the process used by medieval Italian blacksmiths known as *assottigliamento.* Thus the journals are not necessarily "thin," but "hammered." Cf. Taccola, *Taccola and "De ingeneis,"* pp. 76–77, or Taccola, *Liber tertius de ingeneis,* fols. 4r–v; and Taccola, *De ingeneis,* Vol. 2, fol. 15r (left-hand side and text). For the process known as *assottigliamento* see note 5.

[19] Taccola, *De ingeneis,* Vol. 2, fol. 74r; and Taccola, *Taccola and "De ingeneis,"* pp. 78–79; cf. Taccola, *Liber tertius de ingeneis,* fols. 5r–v. For the two-piece construction of these wheels see Taccola, *De machinis,* Vol. 2, fol. 22v (1449). The best examples of these numerous mountings, frequently drawn hurriedly and without detail, are found *ibid.,* fols. 24v, 45r, 71v. Cf. Taccola, *De rebus militaribus,* pp. 164, 242, 348. Although Taccola does not discuss them, the wheels evidently turned on the stubs of fixed wooden axles. Within their sockets is a low-friction substance held in place by four triangular reinforcements, while linchpins run through the stubs to hold the wheels in place. Because of its round, irregular shape, this substance is very likely iron.

[20] In the works of Taccola the depictions of journals are many and frequently show no blocks at all. For the typical journal that depicts a lateral attachment by rivets see Taccola, *De ingeneis,* Vol. 2, fol. 15v (center) (1419–1427). For journals with bearing blocks for the period 1427–1430 see, besides Figure 2, *ibid.,* fols. 35v, 36r. For 1433 consult Taccola, *Taccola and "De ingeneis,"* pp. 78, 86, 106, 142. Cf. Taccola, *Liber tertius de ingeneis,* fols. 5r, 8v–9r, 18v–19r, 39r. For the period between 1434/1438 and 1449 see Taccola, *De ingeneis,* Vol. 2, fol. 96v. Journals and their supports for the year 1449 are found in Taccola, *De machinis,* Vol. 2, fols. 43r, 43v, 45v. Cf. Taccola, *De rebus militaribus,* pp. 234, 236, 244. For a depiction of a journal turning on blocks that may have been drawn after 1449 see Taccola, *De ingeneis,* Vol. 2, fol. 103v (bottom). In at least two instances Taccola draws an axle whose journals have alternative functions: one, a pivot obviously made of iron, turns solely upon a wheel block; while the other, apparently made of wood, rotates within it. Is this pure

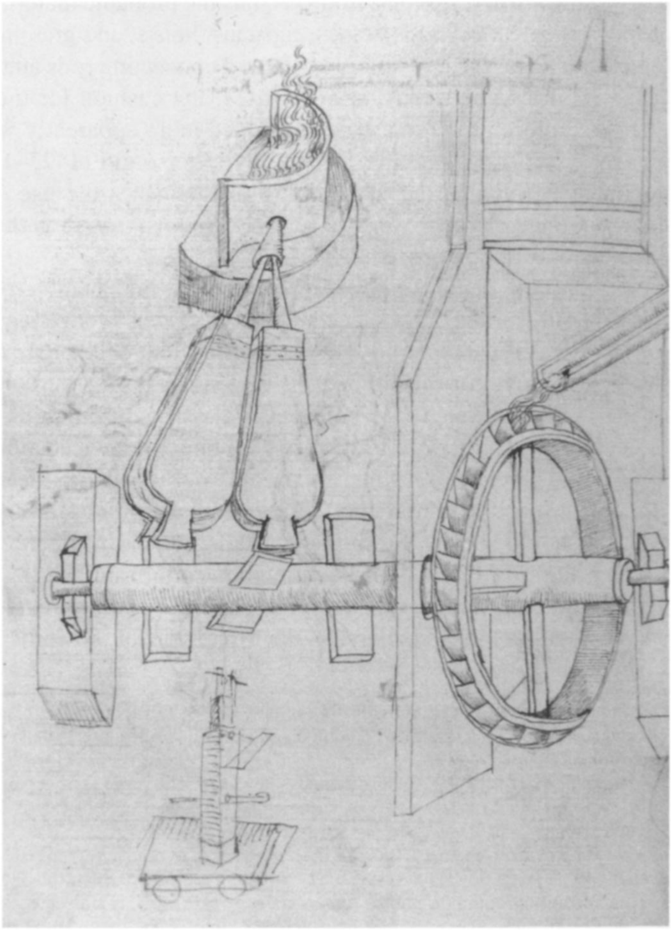

Figure 2. A pair of bellows activated by cams and an overshot waterwheel for blowing air into a furnace (1427–1430). From this "aerial" view, note the journals at the ends of the camshaft. They are knobbed so that they can run more evenly upon the hardwood bearing blocks, which themselves rest on the larger wheel blocks beneath them. The separate drawing below is a rough sketch of a mobile scaling tower with a battering ram (1434/1438–1449). From Mariano Taccola, De ingeneis: Liber primus leonis, liber secundus draconis, addenda, *ed. and trans. Gustina Scaglia, Frank D. Prager, and Ulrich Montag, 2 vols. (Wiesbaden: Ludwig Reichert, 1984), Vol. 2, fol. 30v.*

on iron cushions, but such a conclusion must be stated with caution. The *sollolae,* made of cornel wood, operated in the fourteenth-century grain mills of Turin not only as bearings for horizontal axles but also beneath the spindle, the secondary vertical shaft that led directly to the upper millstone.[21] The hardwood to which Taccola refers could have been employed in similar mechanical situations.

fancy or an indication of the variety of methods that could be used in combining pivots and bearings? See Taccola, *Taccola and "De ingeneis,"* p. 120, or Taccola, *Liber tertius de ingeneis,* fol. 29r (1433); and Taccola, *De ingeneis,* Vol. 2, fol. 105r (right of center) (1434/1438–1449). None of Taccola's journals are winged so that they can be hammered into the end of the axle for greater security. It cannot now be determined when this firmer fit became common.

[21] Dal Verme, in Alliaud and Dal Verme, "Spese di gestione" (cit. n. 13), p. 154.

It would appear that the first of the so-called anonymous Hussite engineers, who composed his notebook between 1472 and 1475, was aware of the benefits of applying iron on iron as a means of reducing attrition. Iron pivots and bearings were probably paired in the horizontal mill whose invention he attributes to "a pope from Rome," and it seems likely that such a coupling occurred at the ends of vertical shafts located in other grain mills, construction cranes, and hoists.[22] He is more precise about his knowledge of low-friction metals when he "envisions" a triangular siege engine with two iron wheels rotating on an iron axle near its front. He also devises a grain mill whose vertical axle, like those of Taccola, is a crankshaft moved manually by a connecting rod; the crankshaft is made of iron, and he recommends that the eye of the wooden connecting rod should be steeled.[23] However, if iron did turn on iron to eliminate friction, it is apparent from his text that wooden journals also revolved on this substance. In a rather complex mechanism for a well hoist, a vertical handwheel rotates a lantern pinion, a small gearwheel with cylindrical bars rather than teeth, that is in contact with a vertical cogwheel above it. The separate axle of this cogwheel carries a drum that winds the rope for raising the container of water. This horizontal axle is made of wood whose journals turn in a V-shaped iron brace with its wings attached at their ends to a transverse beam crossing above. The horizontal shaft of the handwheel and lantern pinion is also composed of wood, and its wooden pivots revolve in the iron plating of the two wooden uprights that support the whole device (see Figure 3). Two cannon hoists demonstrate the same combination, with the horizontal wooden axles of their windlasses revolving in large iron bearing blocks.[24]

We are thus left with an assorted collection. If we accept the information provided by these fifteenth-century imaginative compilers of technological contrivances, iron and wood for pivots and bearings might conceivably have been interchangeable. Such a conclusion can perhaps be verified with reference to the workaday world of Italy at this time. In the 1470s the ironworkers of the Tuscan Casentino were making journals, weighing approximately fifty pounds each, for stabilizing the movement of horizontal axles on the wooden blocks of both fulling mills and trip-hammers that struck iron recently obtained from the furnaces. Leonardo da Vinci himself shows that iron bearings were used: in describing the power of simple friction, he utilized the example of a bare wooden journal that burst into flame as the water between the "sharpened iron" and the journal was removed.[25]

Given the large amount of abrasion that Leonardo's example suggests, the rotation of iron on wood, or wood on iron, at first seems highly problematic. In fact, these pairings

[22] Anonymous of the Hussite Wars, *Technological Illustrations,* ed. Hall (cit. n. 10), p. 34 (date of composition), fol. 18v (attribution). Grain mills: *ibid.,* fols. 22r–v and pp. 171–172. The upper pivots turn in large, apparently iron, blocks. The lower pins would have to have some sort of cushion other than the floor. This would also be the case for the secondary vertical axles, whose pivots (fol. 22r) turn on the floor as well as on a supporting beam and a rudimentary bridge. Cf. fols. 19r–21v, 23r, 24r, and pp. 164–171, 172, 174; see also fols. 36v and 38r, where the second of the so-called anonymous Hussite engineers used blocks of iron for bearings. For Agricola's use of iron sockets for bearings see Figure 1. Construction cranes: *ibid.,* fol. 8v and p. 148; cf. fols. 1r, 2v, 3v, 4v, 6v, and pp. 139, 140–141, 142, 143, 147. Hoists: *ibid.,* fol. 25r and pp. 175–176. The iron pivot at the lower end of the vertical shaft of this earth-moving hoist rotates on a large rectangular platform without any cushion. Presumably such a cushion would be made of iron.

[23] *Ibid.,* fol. 16v and pp. 158–159 (siege engine); fol. 18r and pp. 162–163 (grain mill). Cf. pp. 88, 100–102.

[24] *Ibid.,* fols. 1v, 25v, and pp. 139–140, 176. Cf. fols. 5r (bottom), 6r, and pp. 144–145, 146, where the materials of the axle and the single bearing are not differentiated. The pivots and bearings of other horizontal axles lack enough uniformity with respect to their materials that one can only guess what their composition might be. Aside from the references already tabulated in note 23 and Figure 3, see fols. 2r, 3r, 4r, 8r, 9v, 10v, 15r (lower right), 17v, and pp. 140, 141, 143, 148, 149, 150, 156–157, 159–161.

[25] Muendel, "Mountain Men of the Casentino" (cit. n. 5), pp. 51–55; and Leonardo da Vinci, *The Notebooks of Leonardo da Vinci* (1939), ed. and trans. Edward MacCurdy (New York: Braziller, 1955), p. 600. See also Dowson, *History of Tribology* (cit. n. 1), p. 98.

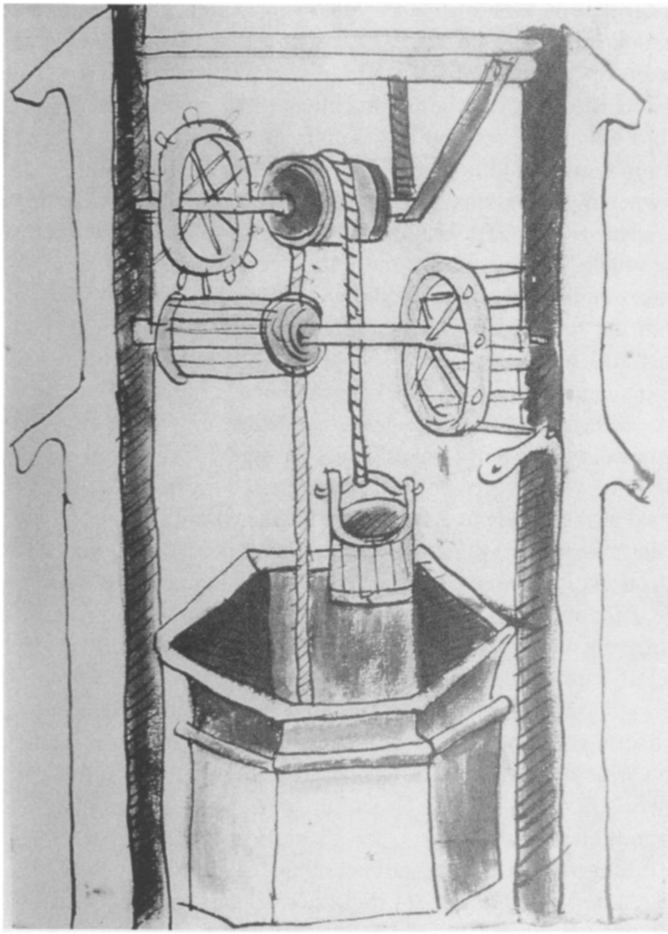

Figure 3. *A well hoist moved by a handwheel and interlocking gears (1472–1475). From Anonymous of the Hussite Wars,* The Technological Illustrations of the So-Called "Anonymous of the Hussite Wars": Codex Latinus Monacensis 197, Part 1, *ed. Bert S. Hall (Wiesbaden: Ludwig Reichert, 1979), fol. 10r.*

are consistent with the idea that medieval machines had to work within strict economic constraints while attaining topmost efficiency. Experiments cannot duplicate the conditions under which the machinery actually operated. Still, when oak runs on wrought iron with the fibers parallel to the direction of movement and both surfaces are considerably polished by wear, a coefficient of friction between 0.126 and 0.168 can be attained under a pressure of approximately 1,108 pounds. On the other hand, when iron runs on wet oak with the grain of the wood traveling parallel to the motion, a less impressive but still low coefficient of 0.243 can be obtained under a pressure of about 1,486 pounds. This resistance can be substantially reduced if iron turns on a greased piece of oak under the same conditions, but with a weight of approximately 1,103 pounds: in this case, a coefficient of 0.072 is achieved.[26]

Still another variation can be added to the combinations so far presented. Iron journals

[26] Morin, *Expériences,* Diss. 2: *Metz, 1832* (cit. n. 8), p. 66.

(*cavigliae*) turning on wooden wheel blocks were found throughout the territory of Florence from at least the fourteenth century. The journals were placed at the ends of the horizontal axles of fulling mills located on the Arno and the Greve rivers, and they operated on the principal shafts of suspension mills and landed undershot and overshot mills at Pulicciano and Tobbiana in the Valdelsa, at Ricorboli just outside the southeastern wall of Florence, at San Donato a Villa near Dicomano, and at Fornace in the mountainous area west of the Monte Falterona.[27] Yet, if we can trust the absence of metal pivots and bearings in the account books for the communal mills of the city of Florence for the years 1378, 1379, and 1382, oaken journals must have rotated on oaken blocks as well. Since the fuller laboring at the mill on the Greve was responsible for acquiring iron journals from the city, the absence of these evidently popular devices for the eighteen runs of this urban establishment does seem strange. When the suspension mill at Ricorboli was assessed on 10 November 1381 there were two entries for the manufacture of journals, one for eight of them and another for one.[28] Surely, if this mill with only a single run included journals among its purchases, the much larger installation at Florence, appraised over a longer period of time, would have shown some evidence of their existence in its records.

Again, it should be noted that wood revolving on wood is by no means a primitive or regressive setup: when dry oak runs against dry oak with the fibers perpendicular to the motion, a coefficient of 0.286 can be reached under a pressure of about 1,990 pounds. When the dry, smooth fibers run parallel to the motion at a pressure of about 440 pounds,

[27] Arno: Archivio di Stato di Firenze, Notarile antecosimiano, R348, fols. 333r–v, 27 May 1325 (Ser Rustico di Moranduccio di Bondone da Firenze): the letting out of "quoddam suum palatium cum tribus cippis gualcheriarum in dicto palatio [cum] arcis ad sodandum et gualchandum pannos fornitis pilis, stelis, mazzis, chavaleriis, astis, cerchiis et chavilglis . . . et cum ghora et aqueduccu . . . in flumine Arni in dicto popolo Sancti Pieri de Quintole locho dicto Girone." The *cavaleriae* may be the diagonal beams that supported and let swing the upright shafts (*astae*) of the horizontally striking hammers (*mazzae*). They could also be devices for hoisting cloth.

Greve: *Ibid.,* Compagnie religiose soppresse, 482, fols. 122v–123r, 11 Feb. 1335: the letting out of "unam domum cum usu curie et putei et cum tribus cippis gualcheriarum et cum piscaria et docciis et aliis necessariis ad gualcandum positam in flumine Grevis in popolo dicte plebis [Sancti Alexandri de Giogolis] . . ." and the fuller must bring back from "civitate Florentie cerchios de ferro et caviglas ferreas . . . ad dicta molendina."

Pulicciano: *Ibid.,* Notarile antecosimiano, I58, fols. 10v–11r, 28 Feb. 1338 (Ser Iacopo di Lapo di Bincio da Certaldo): the letting out "ad utendum . . . [et] faciendum ad sextum" of a broken-down, landed undershot mill "cum duobus palmentis et cum terra ortali . . ." and the miller has acknowledged that he will maintain the same mill "omnibus ipsius conductoris suptibus et expensis [de] martellis, picchonibus, palis de lingno, razcis, nervis et chavigliuolis, holeo et aliis omnibus necessariis." The waterwheels' wooden paddles rather than receptacles identify an undershot type located next to a garden patch. The *nervi* are probably reinforcements for the hubs of the waterwheels, which hold the spokes (*razzi*) in place.

Tobbiana: In 1367 a suspension mill with two runs, one "cum duobus caviglozis bonis de ferro" and the other "cum duobus caviglozis de ferro," was found here; see John Muendel, "The 'French' Mill in Medieval Tuscany," *Journal of Medieval History,* 1984, *10:*215–247, on p. 241.

Ricorboli: Two of the three mills located here in 1383 can definitely be identified as a landed undershot mill ("mulino orbo") and a suspension mill ("mulino penzolo"). The identity of the third, the "mulino di mezzo," is not specifically known, but its parts are much like those of the landed undershot mill. All three have "chavilglie" or "chavilgle." See *ibid.,* pp. 242–243.

San Donato a Villa: Archivio di Stato di Firenze, Notarile antecosimiano, L80, fol. 4v, 22 Dec. 1410 (Ser Lapo di Mazzeo di Amerigo da Prato): the renting out of a probable overshot grain mill "cum terra, castagneto et . . . cum macinis, bozola, stadera, martello et fusolis, palo et caviglis et feris pertinentibus ad molendinum." The *bozzola* is the container for measuring the amount of flour the miller takes as compensation for his labor.

Fornace: *Ibid.,* A92, fol. 125v, 11 Dec. 1351 (Ser Adamo di Cenni da Farneta): the renting out of a probable overshot grain mill whose iron parts and implements "sunt II cavillie ferri, VI fuselli, I palum ferri, II circuli feri in stegolo, duo cirguli ferri in robecchio, II martelli, I nottola, I statera comunis, I bozolla ferri."

[28] Muendel, "Internal Functions of a Florentine Flour Factory" (cit. n. 5), p. 512; and Archivio di Stato di Firenze, Conventi soppressi, 168, 159, fol. 3v: "E fece fare otto chavigle di ferro a Martellaccio fabro. . . . E fece fare al detto Martellaccio una chavigla e due cerchi da rotelle" (Ricorboli assessment).

the coefficient is 0.119; at around 1,742 pounds it is 0.101.[29] If a lubricant is added, the ratio in all cases drops even further. The inner workings of these communal mills demonstrate still another effective means of combating friction through the carefully planned use of wood, an adaptation that may validate the preference for wood running on wood in the machines of this medieval factory. In the gearing systems of these landed undershot grain mills, walnut rollers, known as *rullae,* were employed to interact with teeth made of evergreen oak so that attrition could be reduced as the wheels turned. These resilient, rotatable gear teeth were the forerunners of the wooden cylinders found in Brunelleschi's reversible hoist. They were also significantly represented in the many mills devised by Francesco di Giorgio Martini.[30]

In all, these developments highlight not only the effectiveness of wooden materials interacting to reduce friction, but also the innate ability of medieval Tuscans to recognize the inherent, long-term benefits of wood operating in machines. As is pointed out in George Rennie's third edition of Robertson Buchanan's *Practical Essays on Mill Work and Other Machinery,* wood—unlike iron or steel—"when it is crippled, complains, or emits a sound, and after this, although it is much weakened, it may still retain strength enough to be of service."[31]

By the thirteenth and fourteenth centuries, if not before, English machines were employing brass, with bronze the best of the low-friction metals. Brass bearings, or pillows, weighing as much as sixteen pounds were placed beneath the secondary vertical axles, or spindles, of undershot and overshot grain mills. In windmills whose body, or buck, turned on a sturdy post to meet the source of their power, the same material was used not only for pillows but also for the neck braces that supported the inclined windshafts of these machines. Sometimes brass, as well as steel, formed a replaceable foot for the spindle, and it must be assumed that whichever of these metals was used for this part it ran against a bearing of a different metallic content to eliminate as much resistance as possible.[32] Brass working against wrought iron has a coefficient of friction as low as 0.126, brass against steel 0.139, and steel against bronze 0.137.[33]

[29] Morin, *Expériences* (cit. n. 8), Diss. 1: *Nouvelles expériences sur le frottement, faites à Metz en 1831* (Paris: Bachelier, 1832), pp. 82–83. Cf. *ibid.,* Diss. 2: *Metz, 1832* (cit. n. 8), pp. 17–18, where he repeated his experiments under the same conditions, but on smaller surfaces of contact and with considerably less pressure. At the highest weight, approximately 367 pounds, he obtained a coefficient of 0.326 and attributed the increase to the tearing and charring of the surfaces. For the coefficients at 440 and 1,742 pounds see *ibid.,* p. 14.

[30] Muendel, "Internal Functions of a Florentine Flour Factory" (cit. n. 5) pp. 514–516. Taccola is aware of rollers turning on stationary axles, but they are utilized for hauling quarried columns in a manner suggested by Brunelleschi or for pulling vehicles. For the period 1419–1427 see Taccola, *De ingeneis,* Vol. 2, fol. 1r (bottom). For 1433 consult Taccola, *Taccola and "De ingeneis,"* pp. 98–99, 102, 105; cf. Taccola, *Liber tertius de ingeneis,* fols. 15v, 17v–18r. For drawings probably done after 1449 see Taccola, *De ingeneis,* Vol. 2, fols. 23v, 127r. In regard to the wheels of a four-wheeled wagon supporting an assault weapon, Taccola claims that "Rulli sunt meliores," or "Rollers are better": *ibid.,* fol. 63v (1427–1430). The hatch of a modified bellows, squirter, or fulling mill drawn by Taccola has a roller at its front edge being struck by a revolving cam so that the hatch will rise and fall. The roller, however, appears to be one piece, pivoting on its own axle-ends. See *ibid.,* fol. 40r (1427–1430); and Paolo Galluzzi, "Catalogo," in *Prima di Leonardo,* ed. Galluzzi (cit. n. 9), p. 437. Note that Agricola has an antifriction bronze roller turning on an iron pin, which is used for a stamp that splits cakes of copper: Agricola, *De re metallica,* ed. and trans. Hoover and Hoover (cit. n. 12), pp. 501, 502–503. Cf. Beck, *Beiträge zur Geschichte des Machinenbaues* (cit. n. 1), pp. 161–162.

[31] Buchanan, *Practical Essays on Mill Work* (cit. n. 7), p. 254.

[32] Holt, *Mills of Medieval England* (cit. n. 7), pp. 123–125; and John Langdon, "The Birth and Demise of a Medieval Windmill," *History of Technology,* 1992, *14:*54–76, on pp. 59, 66, 70. See also Leonard Archbutt and R. Mountford Deeley, *Lubrication and Lubricants: A Treatise on the Theory and Practice of Lubrication and on the Nature, Properties, and Testing of Lubricants* (1900), 5th ed. (London: Charles Griffin, 1922), pp. 7–8, 427.

[33] Rennie obtained the figure of 0.126 (brass and wrought iron) at a pressure of 84 pounds; at 192 pounds the

This widespread and efficient use of brass in the vertical mills of medieval England suggests the possibility that it was also employed at the Salisbury and Wells cathedrals for their large clocks, built during the late fourteenth century. Since the verge escapement and foliot balance of these machines regulated wrought-iron gears at least three feet in diameter, the bearings of the frame had to be most effective in overcoming the considerable friction generated by the turning axles. Scholars have thought that the brass bushings, or sleeves, of these clocks as they now stand were added to their wrought-iron frames well after the initial construction (see Frontispiece). However, since around 1385 a close friend of Giovanni de' Dondi described his astrarium, or astronomical clock, with its 107 wheels and pinions, as being made entirely of brass and copper ("toute de laiton et cuivre"), it is not impossible that these bushings were a late fourteenth-century phenomenon.[34]

It stands to reason that, like the high-quality steel at Tamworth, brass, an alloy made of copper and zinc, must have undergone an extensive period of experimentation before makers achieved the balance of ingredients that would enable it to stand up under rigorous demands. One might assume that it was simply a variation of a compound inherited from Hellenistic engineers—who were certainly aware of pivots and bearings made of iron and either copper or bronze—that passed into Europe through the writings of Arabic engineers.[35] But given the lack of evidence for such influence, the manufacture of medieval metallic fittings in the West is more than likely the result of the trial-and-error methods of smiths and millwrights unaware of the intellectual traditions of the past.[36] Changes resulting from such empiricism were certainly occurring with respect to the manufacture and use of both bronze and brass in Italy from the early fifteenth to the early sixteenth century. In 1408–1409 the *sollolae* or bearings at the mills of Turin were made of bronze for the first time. At Florence the vises or nut blocks (*mozetti*) of Brunelleschi's elevated load

coefficient was 0.141. The coefficient of 0.139 (brass and steel) was achieved with a weight of 36 pounds; that at 192 pounds was 0.146. See Rennie, "Experiments on Friction and Abrasion" (cit. n. 8), p. 157. For steel running against bronze see Morin, *Expériences,* Diss. 2: *Metz, 1832* (cit. n. 8), p. 83. Morin's experiments with this combination were all done at a pressure of approximately 2,206 pounds. The coefficients of 0.137, 0.146, and 0.173 come to an average of 0.152.

[34] Dowson, *History of Tribology* (cit. n. 1), pp. 77–79; and Silvio A. Bedini and Francis R. Maddison, *Mechanical Universe: The Astrarium of Giovanni de' Dondi* (Transactions of the American Philosophical Society, N.S., 56[5]) (Philadelphia: American Philosophical Society, 1966), pp. 15, 20, 50.

[35] Hero of Alexandria, *Les mécaniques ou l'élévateur des corps lourds,* ed. and trans. Bernard Carra de Vaux (1894; Paris: Belles Lettres, 1988), p. 115. Cf. Pappus of Alexandria, *Pappi Alexandrini Collectionis quae supersunt,* ed. Frederick Hultsch, 3 vols. (1875–1878; Amsterdam: Adolf M. Hakkert, 1965), Vol. 3, pp. 1116–1117. Iron journals and cushions are found in Vitruvius, *On Architecture,* ed. and trans. Frank Granger, 2 vols. (1931–1934; Cambridge, Mass.: Harvard Univ. Press, 1970, 1983), Vol. 2, pp. 302–303 (10.4.1), 308–309 (10.6.3). For the axles and bearings devised by Arabic engineers see Ibn al-Razzāz al-Jazarī, *The Book of Knowledge of Ingenious Mechanical Devices,* ed. and trans. Donald R. Hill (Dordrecht/Boston: Reidel, 1974), pp. 275–276. See also Dowson, *History of Tribology,* pp. 50–51, 56, 66–68.

[36] The importance of the classical engineering tradition in Western Europe appears to have been limited. See Taccola, *De machinis,* Vol. 1, p. 26; Taccola, *Taccola and "De ingeneis,"* pp. 53–54, 154–157; and Taccola, *De ingeneis,* Vol. 1, pp. 24–27. Cf. Edward Grant, "Henricus Aristippus, William of Moerbeke, and Two Alleged Medieval Translations of Hero's *Pneumatica,*" *Speculum,* 1971, *46*:656–669. Unlike the Islamic philosophical and scientific texts, the technological treatises of Arabic engineers were not translated into Latin. For this circumstance and other possible avenues for technological diffusion see Ahmad Y. al-Hassan and Donald R. Hill, *Islamic Technology: An Illustrated History* (Cambridge: Cambridge Univ. Press; Paris: Unesco, 1986), pp. 12–71, esp. p. 33; and Hill, "Préface: Les oeuvres de Héron et leur context historique," in Hero, *Mécaniques,* ed. and trans. Carra de Vaux, pp. 9–20, on pp. 16–19. Cf. Thomas F. Glick, *Islamic and Christian Spain in the Early Middle Ages* (Princeton, N.J.: Princeton Univ. Press, 1979), pp. 217–247. Writing between 1420 and 1440 in the vicinity of Venice, Giovanni Fontana, the author of *Bellicorum instrumentorum liber,* had a passing familiarity with the work of Philo of Byzantium, Hero, and al-Kindi, particularly regarding the subject of hydraulics. See Giovanni Fontana, *Le macchine cifrate di Giovanni Fontana,* ed. and trans. Eugenio Battisti and Giuseppa Saccaro Battisti (Milan: Arcadia Edizioni, 1984), pp. 10, 53–54.

positioners were made of bronze in order to accommodate vertical screws, evidently made of iron.[37] By the turn of the fifteenth century Leonardo, as we have seen, was pondering the contents of his "mirror metal." Finally, in 1607 the Paduan engineer Vittorio Zonca, in his posthumous work on machines, became the first to record for the learned that brass was the only metal that could run against steel without being consumed.[38] These developments and observations, which presumably drew upon the daily activities of craftsmen and mechanics, indicate the gap in the history of the empirical methods used by medieval artisans of Western Europe who were involved in metallurgy and its applications in reducing friction. One must ask what was happening in areas outside England and Italy during the thirteenth and fourteenth centuries. This gap, which incorporates many other questions related to tribology, can be filled only by patient research, particularly in the archives of Europe and the Near East.

THE APPLICATION OF LUBRICANTS

Medieval machines suffered from a variety of internal stresses that were controlled only by the weight of their parts. This pressure, which Franz Reuleaux called "force-closure," caused machines to start from rest with considerable loads on their bearings, no matter how effective the materials employed at these connections were at overcoming friction once the machines were moving. For the machines to function in an efficient fashion they had to surmount static friction or, as it is sometimes called, the friction of quiescence. Thus if, as we have seen, wrought iron running on wet oak with the fibers of the wood turning parallel to the motion obtains a coefficient of friction as low as 0.243 under a pressure of approximately 1,486 pounds, its coefficient of static friction under the same circumstances is 0.712, nearly three times as great.[39] In other words, machines had to overcome the resistance that made their bearings groan and their parts jerk awkwardly. The best remedy for this problem was lubrication. The first use of a lubricant dates back

[37] Dal Verme, in Alliaud and Dal Verme, "Spese di gestione" (cit. n. 13), p. 154; and Gustina Scaglia, "History of Brunelleschi's Machines," in Frank D. Prager and Scaglia, *Brunelleschi: Studies of His Technology and Inventions* (Cambridge, Mass./London: MIT Press, 1970), pp. 85–109, on pp. 89–93. Howard Saalman, *Filippo Brunelleschi: The Cupola of Santa Maria del Fiore* (London: Zwemmer, 1980), pp. 156, 158, believes that the *mozetti* are bronze teeth that interact with rollers turning on iron pins. However, if five *mozetti* weigh 282 pounds, 2 ounces, as Scaglia reports, one of them could weigh more than 56 pounds, which would be rather large and cumbersome for a bronze tooth functioning in this capacity. Scaglia's interpretation is certainly closer than Saalman's: the vises are essentially bronze bearings, or *bilichi,* enclosed in wooden frames. With reason, Saalman (*ibid.,* pp. 155, 158) sees the *bilichi* as iron axle rods, but such an explanation cannot hold when a blacksmith on 19 Dec. 1421 manufactures four pivots (*perni*) for the "bilichi di bronzi." When Saalman (*ibid.,* p. 166) correctly describes the load positioner of the lantern crane of 1445–1447, he is probably dealing with a Brunelleschian device that has been perfected mechanically and whose parts have been identified more comprehensively. For Taccola's use of *bilichi* see note 18. Eugenio Battisti, *Filippo Brunelleschi: The Complete Work,* rev. Battisti and Emily Lane, trans. Robert Erich Wolf (New York: Rizzoli, 1981), has Brunelleschi's winches being constructed with iron screws that move within a matrix of bronze (p. 362 n. 26).

[38] Vittorio Zonca, *Novo teatro di machine et edificii: 1607,* ed. Carlo Poni (Milan: Il Polofilo, 1985), pp. 80–81. See also Dowson, *History of Tribology* (cit. n. 1), p. 130.

[39] On "force-closure" see Franz Reuleaux, *The Kinematics of Machinery: Outlines of a Theory of Machines,* ed. and trans. Alexander B. W. Kennedy (1876; New York: Dover, 1963), pp. 226–242. See also Usher, *History of Mechanical Inventions* (cit. n. 4), pp. 118, 207–208. On the "friction of quiescence" see William Carter Hughes, *The American Miller, and Millwright's Assistant* (1855), rev. ed. (Philadelphia: Henry Carey Baird, 1878), p. 29. Morin, *Expériences,* Diss. 2: *Metz, 1832* (cit. n. 8), pp. 86–95, refers to static friction as "le frottement des surfaces planes, lorsqu'elles ont été quelque temps en contact" (see p. 91 for the coefficient of static friction at 1,486 pounds). Hughes, an avowed follower of Morin's techniques, may thus have coined the phrase "friction of quiescence." See Hughes, *American Miller,* pp. 27–31. Oliver Evans, *The Young Mill-Wright and Miller's Guide* (1834), 13th ed. (1850; New York: Arno, 1972), pp. 53–58, used the experiments of George Rennie. Cf. Rennie, "Experiments on Friction and Abrasion" (cit. n. 8).

as far as the fourth millennium B.C., when the potters of Ur smoothed the pivot holes of their wheels with bitumen. In ancient Egypt water poured upon wooden planks served to overcome friction so that large stone statues could be moved, while mutton or beef tallow was used to lubricate the axles of Egyptian chariots. Although the boiled-down dregs obtained from the manufacture of olive oil were recommended by Cato the Elder for greasing the axles of farm wagons, lard (*axungia*) and water were the principal lubricants of Roman vehicles.[40] In areas where the terrain was steep, snow, wet grass, and the deliberate application of water allowed sledges to surmount friction and move more readily. Nothing is known about the lubricants of Roman watermills—or, for that matter, about the specific makeup of their journals, bearings, or wheel blocks.[41]

During the medieval period the machines of northern Europe were certainly provided with tallow or suet for dressing their pivots and bearings. In England the use of tallow and grease was common in vertical watermills and post mills alike. The application of suet on the pivots and bearings of the landed undershot grain mills of thirteenth-century Douai is made clear by the requirement that the owners supply "le siu au fier"—"the suet for the iron." The account books of the city of Naumberg for the year 1348 show that money was spent "pro sepo," presumably either to grease the pivots of a new trebuchet's beam or to alleviate stress in the windlass that raised its counterweight.[42]

It has been suggested that rape-seed and poppy-seed oils competed with animal fats as the chief lubricants in the machines of northern Europe during the course of the thirteenth century. This suggestion, which still awaits confirmation, might seem odd, since these unguents have a strong tendency to thicken upon oxidation. After twenty-four hours of exposure to the air, for example, poppy-seed oil becomes hard and dry.[43] Such oils would nonetheless be particularly effective in overcoming static friction because of their ability to spread and their resistance to destruction. At the very low speeds at which the axles of mills turned, the irregularity of the rubbing surfaces could cause cutting and tearing and,

[40] Dowson, *History of Tribology* (cit. n. 1), pp. 23–24, 30–38; Marcus Porcius Cato, *On Agriculture,* trans. William Davis Hooper (Cambridge, Mass.: Harvard Univ. Press; London: William Heinemann, 1935), pp. 94–95 (Ch. 97); and H. A. Harris, "Lubrication in Antiquity," *Greece and Rome,* 1974, *21*(1):32–36. See also J. G. Landels, *Engineering in the Ancient World* (Berkeley/Los Angeles: Univ. California Press, 1978), p. 181. Kenneth D. White, *Greek and Roman Technology* (Ithaca, N.Y.: Cornell Univ. Press; London: Thames & Hudson, 1984), doubts, because of the lack of evidence, that water was a commonly used lubricant in antiquity (p. 137). However, Harris's evidence and suppositions seem convincing. Although water may not have been the most effective of unguents, William John Macquorn Rankine, *A Manual of Machinery and Millwork* (London: Charles Griffin, 1869), does not hesitate to classify it as one of the four principal lubricants, along with oils, soaps, and bitumens (p. 350). Using the research of Morin, he states that water acts as a lubricant on surfaces of wood and leather, but he cautions that its use on a pair of metallic surfaces only increases their friction.

[41] Gösta Berg, *Sledges and Wheeled Vehicles: Ethnological Studies from the View-Point of Sweden,* trans. J. S. Herrström (Stockholm: Nordiska Museets Handlingar, 1935), pp. 64, 78–89; see also Albert C. Leighton, *Transport and Communication in Early Medieval Europe, A.D. 500–1100* (Newton Abbot: David & Charles, 1972), pp. 89–90. Robert J. Spain, "The Second-Century Romano-British Watermill at Ickham, Kent," *Hist. Technol.,* 1984, *9:*143–180, on pp. 150–151.

[42] Holt, *Mills of Medieval England* (cit. n. 7), p. 100; Langdon, "Birth and Demise of a Medieval Windmill" (cit. n. 32), pp. 64–65, 70; Espinas, *Vie urbaine de Douai* (cit. n. 14), Vol. 2, p. 416, Vol. 3, p. 416; and Rathgen, *Geschütz im Mittelalter* (cit. n. 9), p. 615. On one of the counterweight trebuchets of Conrad Kyeser (ca. 1405) a ladder leads up to the fulcrum of the principal beam, where a large, apparently iron bearing is affixed to each of its sides. It would appear that this ladder provides access for lubrication. See Conrad Kyeser, *Bellifortis,* ed. and (German) trans. Götz Quarg, 2 vols. (Düsseldorf: Verlag des Vereins Deutscher Ingenieure, 1967), Vol. 1, fol. 30r.

[43] Dowson, *History of Tribology* (cit. n. 1), p. 72; and Archbutt and Deeley, *Lubrication and Lubricants* (cit. n. 32), pp. 303–310, esp. p. 305. For the rare growth of linseed, rape, and poppy on the manses of medieval peasants see Hans-Werner Goetz, *Life in the Middle Ages: From the Seventh to the Thirteenth Century,* trans. Albert Wimmer, ed. Steven Rowan (Notre Dame, Ind./London: Univ. Notre Dame Press, 1993), p. 144.

eventually, seizing unless the lubricant was especially viscous and durable.[44] If these oils had thickened or hardened at day's end, the journals and blocks could be separated, scraped, and cleaned in preparation for renewed activity. At the mills of fourteenth-century Turin walnut oil, another unguent that congeals rather rapidly when exposed to air, was definitely used for dressing the bearings, as was tallow. Hemp mills and fulling mills were part of the hydraulic complex along the Dora; it would appear that walnut oil was employed to lubricate the bearings of these machines, with their greater lateral stresses, while tallow was reserved for the pivots of grain mills, which did not bear as much pressure. In the fifteenth century Giovanni Fontana of Venice concocted a large, two-wheeled cat, or mobile shelter, for miners who sapped the walls or towers of besieged cities. In order that it move as silently as possible, he recommended that the pivots of its wheels should be well lubricated.[45] What kind of lubricant he had in mind is not known.

THE EARLY USE AND EVOLUTION OF OLIVE OIL AS A LUBRICANT

More than likely, landed overshot and undershot grain mills reappeared in Tuscany during the twelfth century, after an absence of some 550 years. The lubricant for their moving parts was olive oil, one of the most outstanding natural substances for the reduction of friction that the world has known. Unlike tallow and lard, which must overcome an internal shearing stress before they can flow, olive oil spreads easily and thoroughly over the rubbing surfaces. Unlike the drying oils, it does not gum, taking up to seven days to gain as little as 1.7 percent of its weight after exposure to the air. Most important, olive oil stands up extremely well under pressure because of its viscosity and oiliness.[46] Not only can it surmount the thrusts of force-closure, but after the machine is set in motion it also maintains coefficients of friction between 0.07 and 0.08 whether it is running between surfaces of wood and metal, wood and wood, or metal and metal. Perhaps its only weakness is that it can become too acidic, especially if the olives are left to ferment too long before going to the press. This disadvantage was overcome by simply pressing the olives as soon as possible. Within Tuscany and its immediate vicinity, then, olive oil was known as an efficient lubricant that could endure great stress. Although the commune of Florence spent 229 *lire* between January 1378 and March 1379 for approximately 3,251 pounds of olive oil to operate its eighteen landed undershot grain mills, little more than twelve pounds, or less than one-seventh of a barrel, was employed at each run per month. Thus, large quantities of olive oil were not needed to achieve the best performance. The durability of this lubricant is demonstrated by its use in fulling mills, where the strain on the journal is particularly great. This can be seen at Cappiano, in the commune of Incisa, where, at the very end of the thirteenth century, olive oil was applied to the journals at the stamps that processed woolen cloth at two suspension mills. The owner of a fourteenth-century *gual-*

[44] Archbutt and Deeley, *Lubrication and Lubricants,* pp. 56–59. The rotational speeds of a typical waterwheel operating during the Industrial Revolution remained low, fluctuating between 2.5 and 3.7 revolutions per minute; see P. S. Bardell, "Some Aspects of the History of Journal Bearings and Their Lubrication," *Hist. Technol.,* 1979, *4:*1–30, on pp. 1–2.

[45] Dal Verme, in Alliaud and Dal Verme, "Spese di gestione" (cit. n. 13), p. 150; and Fontana, *Macchine cifrate* (cit. n. 36), pp. 89–90. The editors translate "bene inungantur" as "ben oleati" or "well oiled."

[46] Archbutt and Deeley, *Lubrication and Lubricants* (cit. n. 32), pp. 29, 306. Cf. Robert Henry Thurston, *A Treatise on Friction and Lost Work in Machinery and Millwork,* 7th ed. (1885; New York: John Wiley, 1903), pp. 122, 282. On the reappearance of these grain mills in Tuscany see John Muendel, "Mills and Milling," in *Medieval Latin Studies: An Introduction and Bibliographical Guide,* ed. Frank A. C. Mantello and A. G. Rigg (Washington, D.C.: Catholic Univ. America Press, forthcoming). Cf. Muendel, " 'French' Mill in Medieval Tuscany" (cit. n. 27), pp. 215–217.

chiera, located below the *castello* of Rocca San Casciano on the eastern flank of the Alpe di San Benedetto, which separates Tuscany from the Romagna, was obliged to pay for two-thirds of the *oleum operandum* when he leased his mill to another.[47]

The question of how far back the use of olive oil as a lubricant goes is debatable. It was certainly an important article of commerce in the eastern Mediterranean as early as the Mycenaean period; the oil of Miletus, on the west coast of Asia Minor, was particularly renowned after the seventh century B.C.; and by the second and first centuries B.C. the island of Delos had become an important center for its exchange. Aristotle and his associates analyzed the properties of olive oil when they attempted to understand why it was difficult to freeze. They concluded that it contained more air than water, an explanation that they believed accounted for its ability to float on water.[48] Beyond its use as an item for consumption, as a fuel for lamps, and as a salve for athletes, olive oil could act as a base for perfumed ointments, as a remedy for ulcers, as a balm for cancerous ligaments and tendons, as a water repellant for the sinew springs of catapults, or as a preventative for graying hair.[49] In book 15 of his *Natural History* Pliny the Elder presents a long dissertation on the olive and its oil, including a comparison with the "artificial" oils obtained from the wood, leaves, and berries of trees. Going back to the work of Cato, he concludes his discussion by describing the many values of the dregs of olive pressings, making reference to their use as a grease for the axles of wheels. Nothing else regarding the oil's function as a lubricant appears.[50] Only Vitruvius gives some indication of the

[47] For the coefficients of friction see Morin, *Expériences,* Diss. 2: *Metz, 1832* (cit. n. 8), p. 12. Cf. Hughes, *American Miller* (cit. n. 39), p. 28. On the prospect of too much acidity see Archbutt and Deeley, *Lubrication and Lubricants,* pp. 235–244. For the Florentine commune's expenditures see Muendel, "Internal Functions of a Florentine Flour Factory" (cit. n. 5), pp. 512–514.

Archivio di Stato di Firenze, Notarile antecosimiano, G830, part 2, fol. 23v, 16 Dec. 1299 (Ser Guido da Leccio): the letting out of "duo molendina pendola sive pendentia posta in loco dicto Padule et popolo Sancti Laurentii de Cappiano super flumine Arni . . . cum pescharia, aqueductu, gualcheris et quadam navi menatori [*sic*]" and the miller and his son "promiserunt et convenerunt . . . dicta molendina, gualcherias et res pro eo [the owner] tenere . . . et eorum expensis propris rotas et dentes et ferramenta ipsorum molendinorum manutenere et oleum emere de lucro quod ad eorum manus pervenerit ex dictis molendinis."

Rocca San Casciano: *Ibid.,* C303, no pagination (n.p.), (Ser Angiolo di Giovanni di Bartolo Cavriani da Romena): the letting out of "unum molendinum cum palmento ad macinandum et cum gualcheria . . . et teneatur dictus Francischus locator solvere duas partes de tribus partibus oley operandi ad dictam gualcheriam."

[48] On olive oil as a commodity during the Mycenaean period see John Chadwick, *The Mycenaean World* (Cambridge: Cambridge Univ. Press, 1976), pp. 70, 107, 121–122, 156; cf. Harriet Blitzer, "Olive Cultivation and Oil Production in Minoan Crete," in *La production du vin et de l'huile en Méditerranée,* ed. Marie-Claire Amouretti and Jean-Pierre Brun (Athens: École Française d'Athènes, 1993), pp. 163–175, on pp. 167–170, 172. On its exchange at Delos see John Scarborough, *Facets of Hellenic Life* (Boston: Houghton Mifflin, 1976), pp. 64–65; cf. Amos Kloner and Nahum Sagiv, "The Olive Presses of Hellenistic Maresha, Israel," in *Production du vin et de l'huile,* ed. Amouretti and Brun, pp. 119–135, on pp. 132–133, 135. On the experiments of Aristotle and colleagues see G. E. R. Lloyd, *Magic, Reason, and Experience: Studies in the Origins and Development of Greek Science* (Cambridge: Cambridge Univ. Press, 1979), pp. 209–210.

[49] Marie-Claire Amouretti, *Le pain et l'huile dans Grèce antique: De l'araire au moulin* (Paris: Belles Lettres, 1986), pp. 177–196 (base for ointments); John M. Riddle, *Dioscorides on Pharmacy and Medicine* (Austin: Univ. Texas Press, 1985), pp. 66 (remedy for ulcers), 89 (hair); Loren C. MacKinney, "*Oleum Savininum:* An Early Medieval Synthesis of Medical Prescriptions," *Bulletin of the History of Medicine,* 1944, *16:*276–288, on pp. 283, 286–287 (balm); and Landels, *Engineering in the Ancient World* (cit. n. 40), p. 111 (water repellant).

[50] Pliny the Elder, *Natural History,* 10 vols., ed. and trans. H. Rackham, W. H. S. Jones, and D. E. Eichholz (Cambridge, Mass.: Harvard Univ. Press; London: Heineman, 1938–1963), Vol. 4, pp. 288–313. For oil merchants in Rome between the late first century B.C. and the late second century A.D. see Sandra R. Joshel, *Work, Identity, and Legal Status at Rome: A Study of Occupational Inscriptions* (Norman: Univ. Oklahoma Press, 1992), pp. 70, 98, 179, 180, 199 n. 18, 204 n. 15. Cf. Boudewign Sirks, *Food for Rome: The Legal Structure of the Transportation and Processing of Supplies for the Imperial Distributions in Rome and Constantinople* (Amsterdam: Gieben, 1991), pp. 388–391; and Robert Bruce Hitchner, "Olive Production and the Roman Economy: The Case for Intensive Growth in the Roman Empire," in *Production du vin et de l'huile,* ed. Amouretti and Brun (cit. n. 48), pp. 499–508.

possible applications of olive oil as a reducer of friction: it is used either to fashion or to smear the bronze cylinders of water pumps, and it is employed on the slides moved by the keys of water organs.[51]

The utilization of olive oil as a lubricant in medieval Tuscany may antedate the twelfth century, when the landed overshot and undershot grain mills probably returned. Since olive oil was applied to the bearings of fulling mills, such as those at Cappiano and Rocca San Casciano, it may have been put into service as a lubricant as early as the tenth century, when these machines first made their appearance in the documents relating to Italy. In 1299, 1305, and 1381, respectively, suspension mills were supplied with oil at Cappiano, at Catignano in the Valdelsa, and at Ricorboli outside the southeastern wall of Florence. If the suspension mill, run by a right-angled gearing system perched atop stakes driven into the firmest part of the riverbed, originated at the same time as the floating mill, the use of olive oil as an unguent for machines could go back to the sixth century.[52]

One must nevertheless proceed with extreme caution when considering such deductions. Agrarian contracts for Tuscany dating from the eighth to the tenth centuries show that olives were in little demand, and when they were involved in the rents due proprietors, the latter wanted not the oil but the olives themselves for immediate consumption. The items most frequently mentioned in the contracts were wine and pork; the latter, of course, was an excellent source of lard. An increase in the production of olives began in the thirteenth century, as obligations in these agreements required tenant farmers to plant olive-tree seedlings on their *poderi.* But it is not until the fifteenth century that an increase in olive groves and returns in oil was truly perceptible.[53] In short, the manufacture of olive oil was something of a rarity in medieval Tuscany, where the gearless horizontal grain mill predominated until the twelfth century. It would thus appear that the use of olive oil as a lubricant came about purely by chance as landed overshot and undershot grain mills gained greater acceptance, particularly in the territory of Florence. By the fourteenth cen-

[51] Vitruvius, *Architecture,* ed. and trans. Granger (cit. n. 35), Vol. 2, pp. 312–313 (10.7.3), 316–317 (10.8.3). See also Landels, *Engineering in the Ancient World* (cit. n. 40), pp. 76–77 (but he makes the erroneous claim that "olive oil is a poor lubricant for metal surfaces"); and Dowson, *History of Tribology* (cit. n. 1), p. 57.

[52] Paolo Malanima, *I piedi di legno: Una macchina alle origini dell'industria medievale* (Milan: Franco Angeli, 1988), pp. 61–66. For Cappiano see note 47. Regarding Catignano: Archivio di Stato di Firenze, Notarile antecosimiano, R150, n.p., 14 Aug. 1305 (Ser Ricevuto d'Andrea da Castelfiorentino): the renting out of one-quarter "molendini de La Torricella territorii Catignani" with the agreement that the owner "promisit et convenit . . . facere omnis expensis . . . in dicta quarta parte molendini . . . de palis, nervis, razzis, dentibus, oleo et raulis [?] et ferrimentis." This mill has been identified as a suspension mill because, when a quarter of it was sold for 180 *lire* three and a half months earlier, it was described as located "in confinibus Catignani loco dicto ad La Torricella [*sic*] Molendini de Luto" (*ibid.,* 29 Apr. 1305). The muddy environs, like those of the suspension mills described in note 47, would rule out landed overshot and undershot mills and even a floating mill. Moreover, some fifteen years later, when the same mill was held in usufruct, it was called "quoddam molendinum penzolum"; see *ibid.,* D150, n.p., 3 Jan. 1320 (Ser Dono di Bati da Monterappoli). The mention of "palis" may signify that the mill rested on stalks or posts, but it could also be interpreted to mean that it had wide paddles for its wheels. On Ricorboli see *ibid.,* Conventi soppressi, 168, 159, fols. 1r–2v. See also John Muendel, "Medieval Urban Renewal: The Communal Mills of the City of Florence, 1351–1382," *Journal of Urban History,* 1991, *17:*363–389, on p. 383 n. 16.

[53] For the consumption of olives and the frequent mention of wine and pork in agrarian contracts see Bruno Andreolli, "I prodotti alimentari nei contratti agrari toscani dell'alto medioevo," *Archeologia Medievali,* 1981, *8:*117–126, on p. 120; see also Allen James Grieco, "Olive Tree Cultivation and the Alimentary Use of Olive Oil in Late Medieval Italy, 1300–1500," in *Production du vin et de l'huile,* ed. Amouretti and Brun (cit. n. 48), pp. 297–306, on pp. 298–300. On the fifteenth-century increase in olive production see Giuliano Pinto, "Ordinamento delle colture e proprietà fondiaria cittadina," in *La Toscana nel tardo medioevo: Ambiente, economia rurale, società* (Florence: Sansoni, 1982), pp. 157–204, on pp. 189–192. See also Duccio Balestracci, *La zappa e la retorica: Memorie familiari di un contadino toscano del Quattrocento* (Florence: Salimbeni, 1984), pp. 116–117; and Grieco, "Olive Tree Cultivation," pp. 300–303.

tury watermills with vertical wheels rotating their horizontal axles seem to have been lubricated with olive oil on a regular basis. Other records show that olive oil was applied to the journals of a landed undershot mill at Rignano sull'Arno in 1300. Two mills at Ricorboli, one of the type found at Rignano and the other probably following suit, had this lubricant for their mechanisms in 1381.[54] If we accept that this product was used not only at the suspension mill at Catignano in 1305, but also at the landed undershot grain mills at Certaldo in 1327 and at Pulicciano in 1338, providing olive oil for the milling establishments of the Valdelsa had become quite common, even though large amounts were not required. Maggio di Corso, one of the builders of a landed undershot grain mill at Monterappoli sometime prior to 1321, may have been a supplier: at his death his furnishings, besides a footstool, were four large vats, presumably for holding oil for lubrication.[55]

Since sufficient documentation is still lacking, it is difficult to trace with any certainty the use of this extraordinary lubricant outside of Tuscany and its immediate vicinity. Nonetheless, indications of the ongoing employment of olive oil to reduce friction are there. Charles K. Aked has shown that olive oil was used extensively on the gears and bearings of chronometers; this discovery has prompted Duncan Dowson to surmise that its use in mechanical clocks must have begun in the medieval period. Marjorie Nice Boyer has demonstrated that between 1387 and 1389 more than a pound of pig's grease was applied each working day to the pulleys of a pile driver used in the construction of the bridge at Orléans in northern France. At the end of each campaign the pile driver was unbolted and the hardened grease removed so that it would not interfere with work in the next season. By 1513–1514 olive oil had been introduced to help the ropes and pulleys move smoothly and more cleanly.[56]

Recognition of olive oil's effectiveness as a lubricant was by no means universal. Harking back to the Romans' use of *axungia,* lard was applied to the axle-ends of a wagon used in August 1475 when the Florentines were completing the *tribune morte,* or "false arms," of the octagonal drum upon which their cathedral's cupola rested. Throughout the construction of this dome, soap was the principal lubricant for Brunelleschi's reversible hoist, his cranes, and the spire crane of the goldsmith Bruno di ser Lapo Mazzei.[57] During

[54] Archivio di Stato di Firenze, Notarile antecosimiano, G380, part 2, fol. 39v (63v), 13 Aug. 1300 (Ser Guido da Leccio): the letting out of "quoddam molendinum orbicum . . . positum prope pontem Ringnani in flumine Arni cum duobus palmentis, pescharia et aqueductu" and the miller "promisit et convenit . . . suis expensis propris manutenere rotas et dentes ipsi molendini et martellos et mictere oleum quod expedierit." Cf. *ibid.,* fols. 55r (79r), 8 Sept. 1302, and 64v (87v), 5 June 1303. The oil purchased for the suspension mill at Ricorboli was also used for the two other mills associated with it. See notes 52 and 27.

[55] Certaldo: Archivio di Stato di Firenze, Notarile antecosimiano, G106, part 3, fols. 34v–35r, 10 Feb. 1327 (Ser Mazzingo di Pone di Ventura Gennari da Monterappoli): the prior of the church of San Iacopo in Certaldo leases its mill on the bank of the Elsa to another who "promisit et convenit predicto domino Guillelmino . . . predictum molendinum seu molendina tenere et manutenere pro eo et dicta canonica et ecclesia actum ad macinandum de omnibus et singulis infrascriptis rebus et massaritiis ac ferramentis videlicet palis, razzis, nervis, dentibus, oleo, pali [*sic*], nottule [*sic*], fussellis, martellis, piccone et palo de ferro." For Pulicciano see note 27. On the furnishings of Maggio di Corso see John Muendel, "*Mansus,* Machinery, and Co-Proprietorship: The Tuscan Contribution to Medieval Associations of Industry," *Studies in Medieval and Renaissance History,* 1992, *23:*69–113, on pp. 83–85, 110 n. 120.

[56] Charles K. Aked, "Oil for Chronometers," *Antiquarian Horology,* 1968, *5*(12):454–455; and Dowson, *History of Tribology* (cit. n. 1), p. 79. For the use of oils in seventeenth- and eighteenth-century clocks, watches, and chronometers see David S. Landes, *Revolution in Time: Clocks and the Making of the Modern World* (Cambridge, Mass./London: Belknap, Harvard Univ. Press, 1983), pp. 132–144, 171–176. Marjorie Nice Boyer, "A Fourteenth-Century Pile Driver: The *Engin* of the Bridge at Orléans," *Hist. Technol.,* 1984, *9:*31–40, on pp. 36–39.

[57] Saalman, *Filippo Brunelleschi* (cit. n. 37), pp. 294, 255, 261, 283–284, 292. There are eight separate entries

the sixteenth century the royal waterworks of Spain were lubricated with tallow rather than olive oil. In 1603 the tower clock of Winterthur, Switzerland, was dismantled and cleaned by burning the animal fat on its gears and pivots; townspeople danced around the ascending flames. Nevertheless, when the American Robert Henry Thurston, one of a number of late nineteenth-century engineers working to discover the laws of lubrication from purely empirical data, catalogued the fluid lubricants, he indicated that olive oil, among the vegetable species, was "by far most generally used in other countries."[58] During the interval between the beginning of the fourteenth and the end of the nineteenth century, olive oil was widely recognized as an exceptional guard against friction.

THEORY AND PRACTICE

In conclusion, let us turn to the distinguished British scholar G. E. R. Lloyd. In considering the scientific methods of Theophrastus and Strato, he has stated: "the main shortcoming of later Greek physical speculation was not so much a lack of empirical research, nor inadequately debated theories, as a mismatch between the two, the failure to tailor the one to the other." Such a "mismatch" is similarly evident in the science of the late Middle Ages and the Renaissance, as theoretical postures far outweighed empirical investigations. Even if Leonardo da Vinci came very close to sustained experimentation, particularly in his studies of friction, his philosophical and artistic inclinations determined his thinking. So too did the humanist culture of his time. He strove to become part of the literate elite that was detached from society, sustained only by the favors of a despotic *signore,* and critical, if not disdainful, of the common artisan.[59] The machines of the humanist-engineer Francesco di Giorgio Martini, whom Leonardo much admired, were essentially configurations produced within a geometrical framework removed from natural reality. A casual leafing through the drawings of Martini's machines in the *Trattato I* will show that he never includes a pillow for his vertical shafts or axles; they rest upon broad, empty bases as if suspended in midair.[60] Leonardo was more realistic, but not to the point that he could fully incorporate into his investigations the daily mechanical endeavors of craftsmen who

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for the use of soap as a lubricant in the transcribed documents on these pages. On 14 Oct. 1457 six pounds of soap and two pounds of lard were obtained for the lantern crane, and on 8 Apr. 1465 a half pound of lard was purchased for lubricating the pulleys located at the bottom of the lantern (*ibid.,* p. 283).

[58] Thurston, *Treatise on Friction and Lost Work* (cit. n. 46), p. 111. On the royal Spanish waterworks see Reti, "Elements of Machines" (cit. n. 2), pp. 280–281; and Dowson, *History of Tribology* (cit. n. 1), p. 101. For the Winterthur clock see A. J. Duley, "The Liechtis of Winterthur—Clockmakers for Three Centuries," *Antiq. Horology,* 1969, *6*(2):83–90, on p. 87; and Dowson, *History of Tribology,* p. 79.

[59] Lloyd, *Magic, Reason, and Experience* (cit. n. 48), p. 210 n. 421. Note Leonardo's proposed book on friction, in which the action of journals was to be featured; see Leonardo, *Codice Atlantico,* ed. Marinoni (cit. n. 1), Vol. 12, pp. 105–111. For Leonardo's courtly self-image as a painter and inventor see Kemp, *Leonardo da Vinci* (cit. n. 4), pp. 177–179. The best description of the changing character of humanism during the latter half of the fifteenth century remains Lauro Martines, *The Social World of the Florentine Humanists, 1390–1460* (Princeton, N.J.: Princeton Univ. Press, 1963), pp. 286–302 and *passim.* One should not, however, dismiss from this appraisal the architectural writers of the fifteenth and sixteenth centuries who advocated the need for practical experience. Pamela O. Long, "The Contribution of Architectural Writers to a 'Scientific' Outlook in the Fifteenth and Sixteenth Centuries," *Journal of Medieval and Renaissance Studies,* 1985, *15:*265–298, sees the collaboration of Daniele Barbaro and Andrea Palladio on the publication of Vitruvius's *On Architecture* "as paradigmatic of the close relationships between artisans and humanists which underlie the tradition of architectural writings from the time of Alberti" (pp. 292–293). See also Long, "The Openness of Knowledge: An Ideal and Its Context in Sixteenth-Century Writings on Mining and Metallurgy," *Technol. Cult.,* 1991, *32:*318–355.

[60] Vittorio Marchis, "Nuove dimensioni per l'energia: Le macchine di Francesco di Giorgio," in *Prima di Leonardo,* ed. Galluzzi (cit. n. 9), pp. 113–120, on pp. 113–115; and Francesco di Giorgio Martini, *Trattati di architettura ingegneria e arte militare,* ed. Corrado Maltese, 2 vols. (Milan: Il Polifilo, 1967), Vol. 1.

of necessity had to be economically scrupulous. Although Leonardo considered grease a lubricant, in his accounts of lubrication he added millet seeds to a thin layer of that substance to satisfy—rather impractically—his theoretical conclusion that balls or rollers were the only way to overcome friction. When he sought bearings for some of his more elaborate machines, diamond, crystal, and emery were the esoteric materials that he chose.[61] The methods used by common artisans surviving in a stringent medieval economy, on the other hand, reveal the truest empiricism. In the work of these artisans and their successors—in the act, the very doing, of science—theory and practice coalesced. The efforts of those who discovered ordinary materials and substances to surmount attrition in medieval machines may have reached fruition in the nineteenth-century inductive thinking of engineers who solved problems regarding the journal bearings of railroad trains, the launching of ships on slipways, and the deficiencies of the newly found mineral oils. But the cumulative effect of these medieval endeavors was at work even earlier, whether "tailored" to the deliberations of the Paduan engineer Vittorio Zonca or to the abstractions of the eighteenth-century French physicist Charles Coulomb, for whom the array of problems concerning friction was a deep concern.[62]

[61] Leonardo, *Notebooks,* ed. and trans. MacCurdy (cit. n. 25), pp. 600–601 (millet seeds). Dowson, *History of Tribology* (cit. n. 1), p. 98, includes this material, but he does not comment on the millet seeds. Enzo O. Macagno, "Mechanics of Fluids in the Madrid Codices," in *Leonardo e l'età della ragione,* ed. Enrico Bellone and Paolo Rossi (Milan: Scientia, 1982), pp. 333–374, states: "There are some comments about viscosity in his [Leonardo's] notes, but without much fluid-mechanical significance" (p. 338). For the "esoteric materials" see Leonardo, *Codice Atlantico,* ed. Marinoni (cit. n. 1), Vol. 1, pp. 195–196, Vol. 9, p. 227, Vol. 12, p. 88. Cf. Silvio A. Bedini and Ladislao Reti, "Horology," in *Unknown Leonardo,* ed. Reti (cit. n. 2), pp. 240–263, on p. 253. Note that four ounces of emery were obtained by the Opera di Santa Maria del Fiore on 22 Nov. 1457 to polish the female screw of the lantern crane on top of the cupola of the Florentine cathedral; see Saalman, *Filippo Brunelleschi* (cit. n. 37), p. 283.

[62] Bardell, "Journal Bearings and Their Lubrication" (cit. n. 44), pp. 1–30 (trains); Rennie, "Experiments on Friction and Abrasion" (cit. n. 8), p. 155 (ships); and R. Mountford Deeley, "Lubricants," *Encyclopaedia Britannica,* 11th ed., 29 vols. (1768–1771; New York: Encyclopaedia Britannica, 1911), Vol. 17, pp. 87–89, on p. 88. See also Archbutt and Deeley, *Lubrication and Lubricants* (cit. n. 32), pp. 94–107. On Coulomb see Dowson, *History of Tribology,* pp. 210–233, 535–542.