Indian Journal of History of Science, 35.3 (2000) 245-274

JOSEPH NEEDHAM AND THE HISTORY OF INDIAN TECHNOLOGY

IRFAN HABIB*

(Received 11 September 2000)

The paper studies the relevance of the contributions of Joseph Needham to the history of Indian technology, especially in respect of milling, waterlifting devices, worm-gearing, crank, scutch-bow, spinning wheel, liquor distillation, zinc separation and decimal notation. In all these matters, Needham's insights are set against the evidence that has been gathered since his time.

Key-words: alcohol, cotton-gin, crank, distillation, draw-bar, milling, Needham, noria, numerical notation, *sāqia*, scutch-bow, spinning-wheel, zinc.

The great venture of the late Joseph Needham, the publication of the monumental series, *Science and Civilisation in China*, began in 1954. As the volumes came out it became clear that Needham was not simply concerned with the development of science and technology in China, but wished to set it in a worldwide context, with special attention paid to inter-cultural exchanges. It, therefore, became necessary for him to establish the sequence of developments that had taken place in civilisations other than the Chinese. While for Europe there was a vast amount of work already done, whose results he could use, this was by no means the case with India, Iran and Central Asia. And yet Needham extensively explored the scientific and technological aspects of the Indian and Islamic civilisations, going to texts and many out-of-the-way secondary sources. His statements on India, often occurring as asides, were never carelessly made, and invariably gave a critical

* Professor of History (Retd.), Badar Bagh, Civil Lines, Aligarh-202001.

assessment of the existing state of research;[1] and he often gave good guidance on areas that needed to be explored.

In this paper I offer some notes on the questions taken up by Needham relating to the history of Indian technology. I confine myself to the observations made by Needham himself, overlooking those by the independent authors of the volumes in the *Science and Civilisation* series;[2] and, with Needham too, the coverage is partial, relating to the history of milling, water-lift, certain mechanical devices and craft tools, distillation, metallurgy (zinc), and the representation of numbers. This limited survey necessarily leaves out other very interesting aspects and phenomena such as cavalry equipment and the "gun-powder epic" (the latter covered in Vol.V(7)), navigation (Vol. IV(3)), and so on. But even so, I hope that these notes will serve to indicate how much Needham has enlightened us

---

[1]Some twenty-five years ago, I went into a Paris coffee-shop with no other ambition than to have a *darshan* of the *savant*. He put me at ease with words of high praise for P. K. Gode; I was surprised at how much he recollected of Gode's various hypotheses, from the stirrup to distillation.

[2]The volumes of this series of which Needham is either the author, or the main author, are:

I *Introductory Orientations*, Cambridge, 1954.
II *History of Scientific Thought*, Cambridge, 1956.
III *Mathematics and the Sciences of Heavens and the Earth*, Cambridge, 1959.
IV(1) *Physics*, Cambridge, 1962.
IV(2) *Mechanical Engineering*, Cambridge, 1965.
IV(3) *Civil Engineering and Nautics*, Cambridge, 1971.
V(2) *Spagyrical Discovery and Invention: Mysteries of Gold and Immortality*, Cambridge, 1985.
V(3) *Spagyrical Discovery and Invention: Historical. Elixirs to Synthetic Insulin*, Cambridge, 1976.
V(4) *Spagyrical Discovery and Invention: Apparatus, Theories and Gifts*, Cambridge, 1980.
V(5) *Spagyrical Discovery and Invention: Physiological Alchemy*, Cambridge, 1983.
V(6) *Military Technology: Missiles and Sieges*, Cambridge, 1994.
V(7) *Military Technology and the Gunpowder Epic*, Cambridge, 1986.
VI(1) *Botany*, Cambridge, 1986.

I trust my list is complete.

on the technological aspects of our history and how valuable his insights have been for furthering research in a critical (and hopefully non-chauvinistic) manner.

DRAW-BAR AND ROTARY QUERN

I will begin with what I take to be a very pregnant observation by Needham. After describing the olive-crushing mill of classical Greece (the *trapetum*, going back to fifth century BC) and its successor, the rotary Greek and Roman *mola aleria*, he notes the disappearance of this mill in Europe, but draws attention to the fact that "it has an analogue, the origin of which is quite unknown, in the oil mills of India, which consist of a deep annular trough (like the *mortarium*) in which a pestle-shaped crusher is carried round by an animal pulling a radial bar (like the *cupa*)" (IV(2), p.203).[3] In other words, the Indian oil mill incorporated the trough of the Graeco-Roman olive mills, modifying it in order to make it circular, and providing it with a draw-bar for the employment of cattle-power.

Needham confesses that the origins of the Indian mill are "quite unknown"; but his own detection of its affinity with the classical olive-mill raises the question of origins of both of its additional elements, the rotary mill and the draw bar.

Of these the rotary mill seems to appear almost simultaneously in Mediterranean Europe and in China by second century BC (*Science and Civilisation*, IV(2), pp. 187-90). Having established its early presence in China, Needham is concerned over the question whether these could be two such independent inventions made on the two opposite sides of the

---

[3] It may be noted that both the *trapetum* and the *mola alearia* described by Needham here, pp. 202-3, had a longitudinal trough, whereas in the Indian oil mill, it is a circular cavity shaped like a sand-glass, int › which a bulb-like pestle connected with the draw bar is inserted. The cavity contains oil-seeds which are pressed by the pestle as it rotates within the mortar. See the description in Francis Buchanan, *A Journey from Madras through the Countries of Mysore, Canara and Malabar* [1800-01], London, 1807, I, pp. 228-29, with Plate IX, figuring the mill, opposite p. 228; and George A. Grierson, *Bihar Peasant Life*, orig. ed., 1885, reprint, Delhi, 1975, pp. 46-49, with drawing of the mill between pp. 46-47.

Old World, and his own predeliction is for a common earlier source, possibly "Persia or Mesopotamia" or even "the Indus valley" (pp. 190-91). These speculations should be pursued; but the evidence from Taxila, considered in the light of Needham's own scheme of evolution of the mills, shows that India probably played no part in the origins of the rotary mill, but received it some seven hundred years after its appearance in the Mediterranean area and China.

At Taxila the earliest querns found were not rotary: these were either "the stool quern with four legs" found at the Bhir mound (*ca.* 200 BC), or the simple saddle querns found at Sirkap (first century AD).[4] One example of what Marshall calls "circular grinding mills" was also found at Sirkap assignable to the first century AD ("Śaka-Parthian" times).[5] But what Marshall has described as rotary mills, could only have moved in half-circles through manual push-and-pull action. As Lynn White points out, wherever the upper stone (especially when small) has two holes to receive peg-handles, such reciprocal action should be assumed.[6] Marshall's mill, No. 27 from Sirkap, which is assigned by him to the first century AD, has indeed two such peg-holes, both inclining and not vertical. What is called a "crushing mill" of the same date (Marshall's Nos. 30, 31) has the groove for a beam across it, which must have projected out on both sides. As Lynn White says, the beam, found in Roman mills, required reciprocal action with the beam ends serving for handles for both hands.[7] This would be true also of No. 29 from Taxila belonging to the fifth century, which has a similar provision for a handle-beam. The truly circular mill is then Marshall's No. 28, which comes from the Kunala monastery, dated to fifth century AD. Its upper stone is wholly preserved and has one socket only for the peg-handle; and

---

[4] John Marshall, *Taxila: An Illustrated Account of Archaeological Excavations*, Cambridge, 1951, II, pp. 485-6. The claim that a "rotary quern" has been found at Lothal, the Gujarat Indus-Culture site, has been correctly dubbed "suspect" by H. D. Sankalia, *Prehistoric and Historic Archaeology of Gujarat*, Delhi, 1987, pp. 49-50.

[5] Marshall, *Taxila*, op.cit., II, pp. 485-6.

[6] Lynn White Jr., *Medieval Technology and Social Change*, Oxford, 1962, p. 108.

[7] Ibid., p. 108. Lynn White supposes the mills with beams to have been earlier than mills with handles.

this is practically vertical. (See Fig.1, for reconstructions of all the Taxila mills).[8]

The fifth century is thus the earliest date for the appearance in India of both the rotary mill and the vertical peg-handle.[9]

The other element in the Indian oil-mill that we have to consider is the draw-bar. It is seldom realized that after the plough and the cart, the draw-bar has been the most important device for the exploitation of animal power, whether for threshing, lifting water (see below under Noria and Sāqiya), milling sugarcane, or, ultimately, driving machinery. Schioler, who investigated its origins, notes the appearance of the "circular track" in the Mediterranean area by the second century BC.[10] It was a necessary adjunct to the "Pompeian mill", driven by a donkey (*mola asinaria*) whose appearance literary evidence places in the second century BC and archaeological, in around 70 AD (*Science and Civilisation*, IV(2), p. 187). In China, Needham (p. 193) traces a reference to horse-drawn mills (which must then be rotary, a draw-bar being implied) to the second century AD. Here, again, the puzzle faces us of diffusion *versus* independent invention between the Roman world and China.

As far as a common source for the draw-bar is concerned, here too, on the basis of evidence as it stands at present, India is not in the running at

---

[8] Marshall's descriptions of the specimens are in *Taxila*, op. cit., Vol. II, pp. 487-88; the photographs are in Vol. III: No. 28 = Plate 143*h*; No.30 = Plate 143, *e,f,g*. Marshall's artist's reconstructions of Nos. 29 and 30 figured on Plate 140 of Vol. III need to be corrected by eliminating the vertical handle set on the wooden beam, since once the beam was laid across the upper stone in a deep groove, the projections of the beam on either side would have given a much better hand-hold to the miller than two vertical peg-handles set on either side of the beam. In any case, there would be no need to have a deep groove cut for a beam in the upper stone for bearing a vertical peg-handle, which could just have been put directly in a hole on the stone.

The artist's reconstruction of No. 27 in Marshall, III, Plate 140, should show the outline of a second reclining handle on the right side in conformity with the description of the mill in Marshall, II, p. 487. Our Fig.1 incorporates these modifications.

[9] Cf. Lynn White, *Medieval Technology and Social Change*, p. 109n.: "I do not know when the vertical peg-handle reached India."

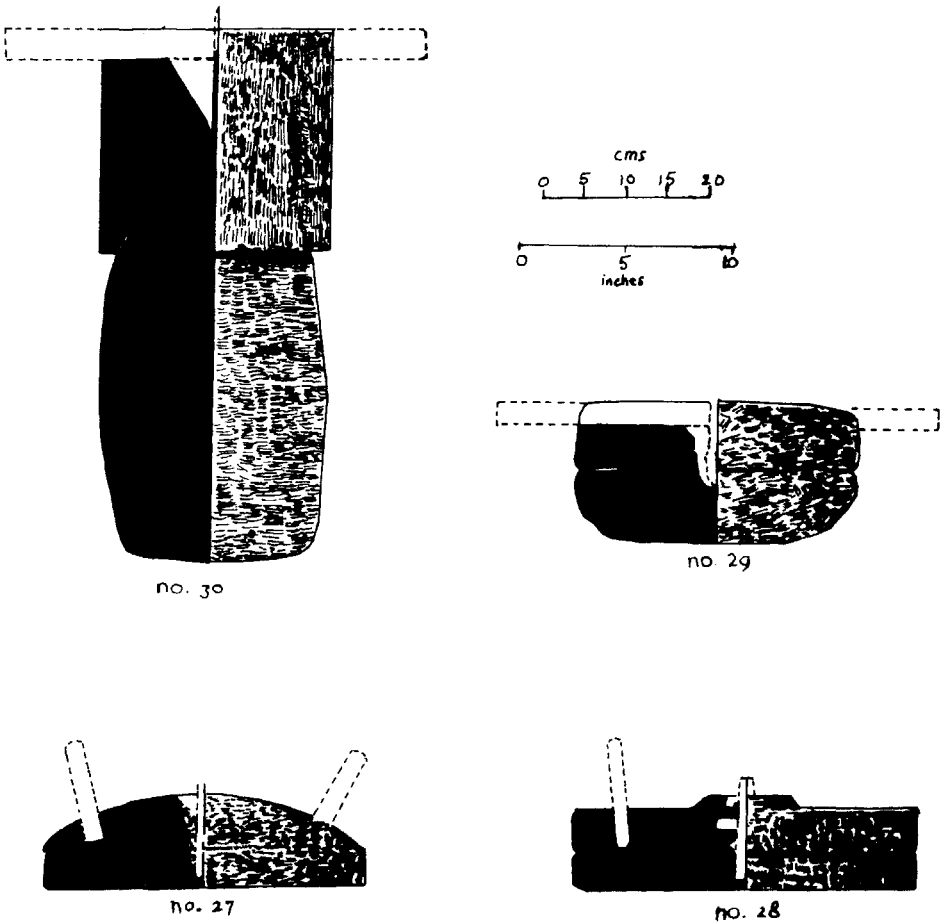


Fig. 1 : Taxila semi-rotary and rotary Mills as drawn in John Marshall., *Taxila*, III Plate 40, but with his reconstructions modified.

all. When even the hand-driven rotary mill is not attested before the fifth century AD, we can hardly look for a draw-bar earlier here. Lallanji Gopal points out that the dictionaries *Abhidhānaratnamālā* and *Vaijayantī* define *meḍhī* as the post on the threshing floor "round which cattle turn to thresh out grains"; and that the *Rāmacarita* describes threshing "by bullocks which went round and round."[11] Of these texts the *Abhidhānaratnamālā* is assigned to *ca.* 950, the *Vaijayantī* a century later.[12] The *Rāmacarita* of Sandhyākaranandin, which Gopal cites, describes the feats of King Rāmapala of Bengal, and so is no earlier than *ca.* 1100.

There is earlier evidence for a rotary oil-mill, which might, however, have been manually worked; but it *could* have been an ox-drawn mill as well. K. T. Achaya draws our attention to the term *tailika-yantra-cakra*, the "oil-mill wheel," in the *Bhavisya Purāṇa*, for which he gives the date *ca.* 500 AD. This could be related to Tamil *cekku* found in two Tamil texts assigned respectively to the seventh and eighth century, there used for an oil-mill. This then must have been rotary, since *cekku* is surely derived from Prakrit *cakka*, Sanskrit *cakra*, whence also modern Hindustani *cakkī*, the rotary mill.[13] From our analysis of the Taxila material, it is obviously possible for a manual oil-mill to have become rotary by the sixth century, as a version of the Taxila rotary quern of the fifth century. But it still would not, as we have said above, attest the draw-bar and use of animal power.

In view of this ambiguity in our early evidence, we may be allowed to consider an inscription at Baijnath in Himachal Pradesh, dated Śaka 726 (804 AD): here we have the donation of an oil mill (*tailotpīḍayantra*, "oil crushing instrument") to a Śiva temple by its two owners to provide oil for

---

[10] Thorkild Schioler, *Roman and Islamic Water-lifting Wheels*, Odense, 1973, p. 168.

[11] Lallanji Gopal, "Technique of Agriculture in Early Medieval India (c.700-1200 AD)," *University of Allahabad Studies* (Ancient Indian History Section), Allahabad, 1963-64, p. 36.

[12] A. Berriedale Keith, *A History of Sanskrit Literature*, London, 1920, p. 414.

[13] K. T. Achaya, "Indian Oilpress (Ghani)," IJHS, 27(1992) 10-11; idem, "Technology of Food," in *History of Technology in India*, Vol. I, ed. A. K. Bag, New Delhi, 1977, p. 468.

lamps.[14] Though the apparatus is not defined, no one would surely have recorded such a donation if it had been a manually worked mortar-and-pestle (let alone a saddle-quern). The only apparatus one can think of is the oil mill proper with its *mortarium* and *cupa*, and the bullock to drive it: only such an apparatus would surely be worth such formal a mention. If so, the draw-bar too must have arrived in this hilly region by *ca.* 800 AD.

We can now return to Needham's insightful comparison between the Indian oil mill and the classical olive-mill apparatus. We can see that the origins of the different parts of the Indian mill are probably all Hellenistic derivation: the trough, as an "analogue" as Needham puts it; and the beam-topped push-and-pull and then the rotary mill, coming through Taxila, which was practically a Hellenistic outpost in India, almost as certainly. Only the line of transmission of the draw-bar remains to be traced. But the Indian evidence for its appearance is so late, even when it is distantly implied, as at Baijnath, that one can practically assume that here too we have probably a Mediterranean source at work, though a transmission from China cannot be absolutely ruled out.

NORIA AND SĀQIYA

In the very few studies of the history of water-lifting devices in India, such as Ananda K. Coomaraswamy's pioneering note on the Persian wheel,[15] there has been a lack of distinction between different kinds of water-wheels, so that all references to a water-wheel were deemed by Coomaraswamy and others to stand for the Persian wheel, which is, in fact, a geared *sāqiya*. A. P Usher drew attention to the confusion between the two forms of water-wheels, viz., "the noria or Egyptian wheel and the chain of pots".[16] Needham, in *Science and Civilisation*, Vol. IV(2), gave a clear definition of the two forms, the noria having the containers fixed to the rim of the

---

[14] G. Buehler, "The two *Prasastis* of Baijnath," *Epigraphia Indica*, I, 115, 118.

[15] Ananda K. Coomaraswamy, "The Persian Wheel," *Journal of the American Oriental Society*, 51 (1931), 283-84 His note was followed by a paper by Berthold Laufer, "The Noria or Persian Wheel," *Oriental Studies in Honour of Cursetji Erachji Pavry*, ed. A. V. W. Jackson, Oxford, 1933, pp. 238ff.

wheel, and the *sāqiya* on the rope or chain flung over the wheel (p. 356) (see Fig. 2). Having done so, he was able to follow up the evidence gathered by Coomaraswamy and Laufer, and argue that the earliest water-wheel in India was the noria, and that, moreover, India was probably the country of origin of this device (pp. 361-62).

The reasons he adduced for this conclusion were two-fold: first of all, the noria was in use in the Hellenistic world in the first century BC and in China in the second century AD, and this proximity of date in such distant civilisations suggested an intermediate source of diffusion. Secondly, he located the earliest recorded reference (derived presumably from Coomaraswamy) to the noria in the term *cakkavaṭṭaka* (turning wheel) used in the *Cullavagga Nikāya* (assigned to *ca.* 350 BC) for one of the three permissible modes of water-lift. Though these details do not appear in Needham, this term was actually glossed by Buddhaghoṣa (fifth century AD) as *arahaṭṭaghaṭīyanta*, which in turn was explained as "a well-wheel with water-pots attached to its spokes" by Kassapa (twelfth century).[17] It is clear that since *ara* means "spoke" and *ghaṭa*, "earthern pot", *araghaṭa* or, in its Prakrit forms, *arahaṭṭa* or *arahaṭṭaghaṭī*, must mean a wheel "with earthen pots on the spokes", so that Buddhaghoṣa's explanation, even without Kassapa's late commentary, is sufficient to show that at least he conceived the *cakkavaṭṭaka* as a noria. L. Gopal cites a passage from the earliest version of the *Pañcatantra*, datable to *ca.* 300 AD, which speaks of a man operating an *araghaṭṭa* (*araghaṭṭavāha*),[18] so that this term, which must originally have been used for the noria, is of a very early date indeed. On the other hand, there is still no firm evidence in India for the chain of pots or "potgarland" (to use Schioler's terminology)[19] earlier than the sixth century, when Yaśodharman's Mandasor inscription dated 589 in the Mālava era (= 532

---

[16] A. P. Usher, *A History of Mechanical Inventions*, Boston, 1959, p. 129.

[17] V. Treckner, W. Andersen, H. Smith and Hendriksen, *Critical Pali Dictionary*, I, Copenhagen, 1948, p. 423.

[18] Lallanji Gopal, *Aspects of History of Agriculture in Ancient India*, Varanasi, 1928, p. 127.

[19] Thorkild Schioler, *Roman and Islamic Water-lifting Wheels*, p. 15. His definition of "noria" as a geared water-wheel with short shaft introduces an unnecessary confusion in the terminology, and has not been followed here.

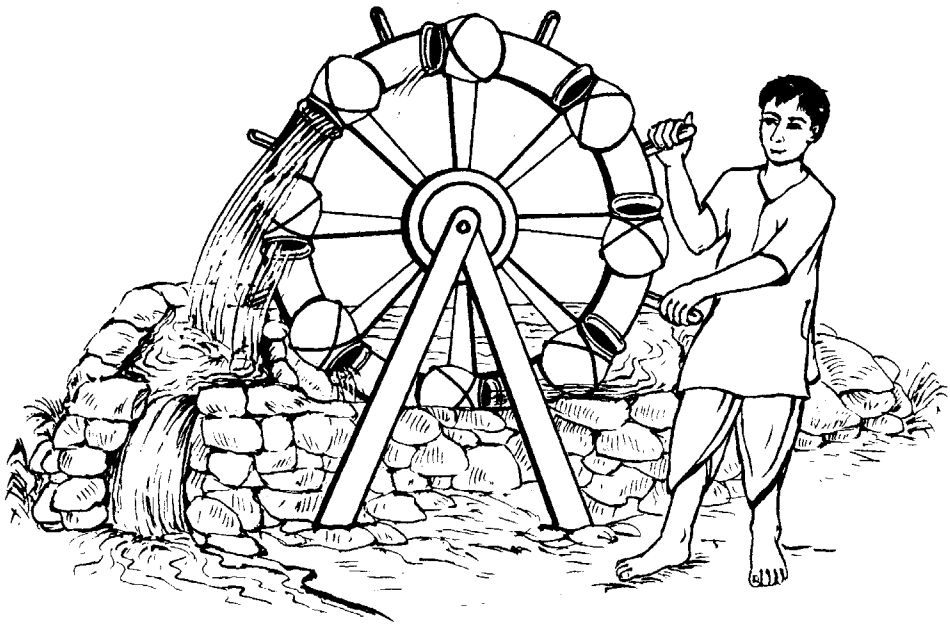


Fig. 2 (a) Noria

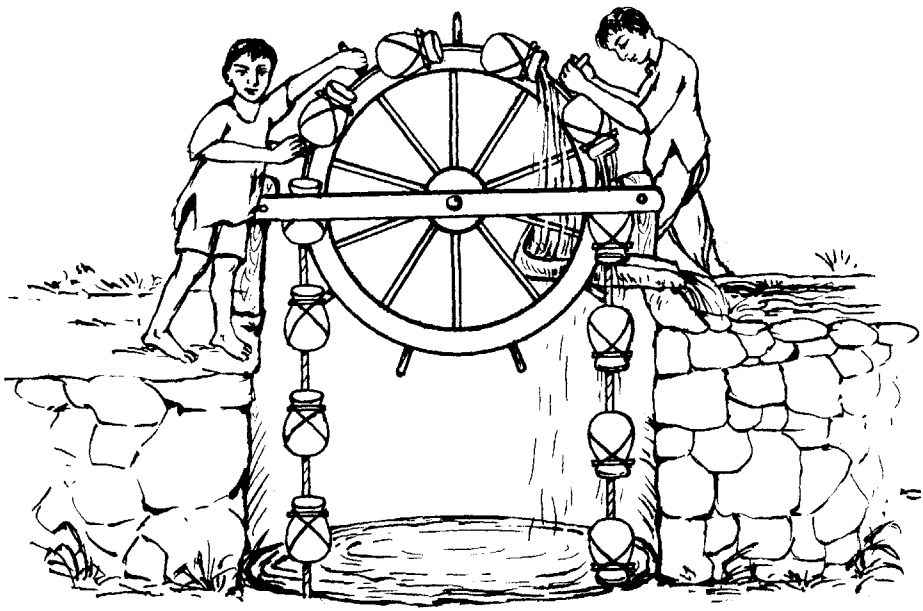


Fig. 2 (b) Sāqiya (without Gearing)

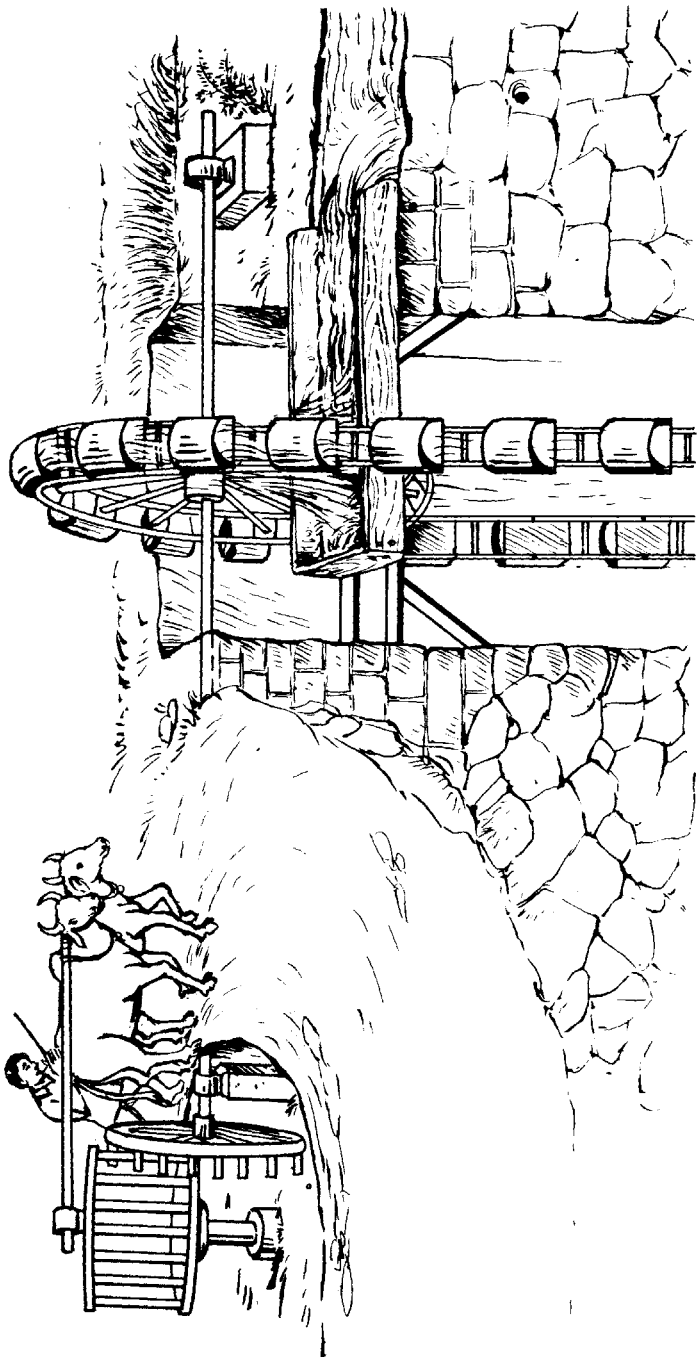


Fig. 2 (c) Sāqiya (with Gearing)

AD) first attests it.[20] With Bāṇa in the next century, the references to the potgarland become fairly numerous ("rosary like the rope on which the pots are placed," etc.).[21]

Gearing is not yet present, for Bāṇa says explicitly that both the "rosary" and the "water-pot device" (*ghaṭī-yantra*) were turned by the right hand.[22] It must be remembered that human drive would imply vertical rotation (and so no gearing), while animal power, usable only with horizontal rotation, needed gearing to convert the horizontal into vertical motion. The well-known Mandor frieze (twelfth century) indeed shows a wheel with a potgarland worked by two men, while water comes out for camels to drink (see Fig. 3).[23] There is naturally no gearing here. The earliest explicit description of the gearing mechanism of the "Persian wheel" or geared

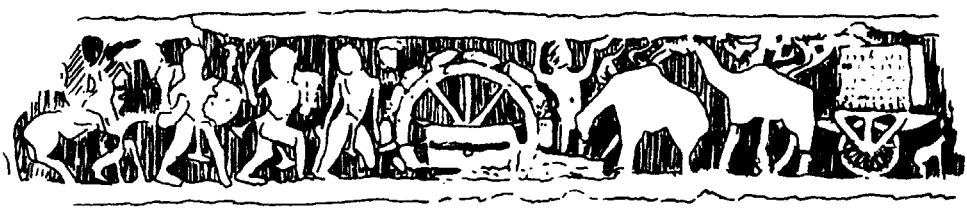


Fig. 3 : Sāqiya, without Gearing, Mandor Frieze, 12th Century.

---

[20] Cf. M. C. Joshi, "An Early Inscriptional Reference to the Persian Wheel" in: *Professor K. A. Nilakanta Shastri 80th Birthday Felicitation Volume*, pp. 214-17. Joshi proposes a modification of the translation of this inscription as given in J. F. Fleet, *Corpus Inscriptionum Indicarum*, III: Gupta Inscriptions, Calcutta, 1888, pp. 150ff.

[21] *Harṣacarita*, ed. P. V. Kane, 2nd ed., Delhi, 1965: *Ucchvāsas* I-III, p. 47, & Notes: *Ucchvāsas* I-III, p. 203; *Ucchvāsas* IV-VIII, p. 84, & Notes: *Ucchvāsas* IV-VIII, p. 246.

[22] Ibid., *Ucchvāsas* I-III, p. 47.

[23] J. H. Marshall and Daya Ram Sahani, *Archaeological Survey of India: Annual Report, 1909-10*, Calcutta, pp. 97-98, with illustration. This frieze has been often misinterpreted as showing a Persian wheel (= geared *sāqiya*), e.g. R. Nath, "Rehant versus the Persian Wheel," *Journal of the Asiatic Society (of Bengal)*, 12 (1970) 83, and T. M. Srinavasan, "Water-lifting Devices in Ancient India: their Origin and Mechanisms," IJHS, 5 (1970) 387-88.

sāqiya is still that of Bābur (d. 1526).[24] (See Fig. 4 for a sixteenth-century depiction.)

We can thus add much to Needham's suggestion by postulating a chronological sequence in three stages:

1. Noria alone, fourth century BC to fourth century AD.

2. The pots previously attached to the spokes and rim now transferred to the chain ("potgarland") (sixth-seventh century); the use of this ungeared *sāqiya* attested, twelfth century.

3. Introduction of the gearing mechanism, and thereby the full-fledged *sāqiya* or Persian wheel, making possible the use of animal power, some time before 1500 AD.

Despite elaborate arguments to the contrary, like those of L. Gopal,[25] where an Indian origin for the *sāqiya* is claimed, Needham's suggestion that India first only had the noria has stood the test of subsequent research fairly well. There seems to be yet no indication that at about 350 BC any trace of the noria was to be found in any civilisation other than India, so that Needham is also probably right in ascribing an Indian origin to the noria.

WORM-GEARING AND CRANK

With almost no materials in his hand relating to the history of worm-gearing in India, Needham (*Science and Civilisation*, IV(2), pp.122-24) yet proposed that the device originated in India. His argument was based on the presence here of the *charkhī* or cotton-gin, with two elongated worms serving to turn its rollers in contrary directions. Noting its presence in Indo-China and Xinjiang, Needham further speculated that it reached China

---

[24] Zahīruddīn Muḥammad Bābur, *Bāburnāma*, Turki text, ed. Eiji Mano, Kyoto, 1995, p. 439; 'Abdu'r Raḥīm's Persian translation (AD 1589), British Museum, Or. 3174, f.376b; English translation (slightly defective here) by A. S. Beveridge, London, 1921, II, p. 486.

[25] Lallanji Gopal, op. cit., pp.122-24 and passim.

Fig. 4 : Geared *Sāqiya* depicted in Niū

Fig. 4 (a) From a Painting by Sānwla, f. 294a

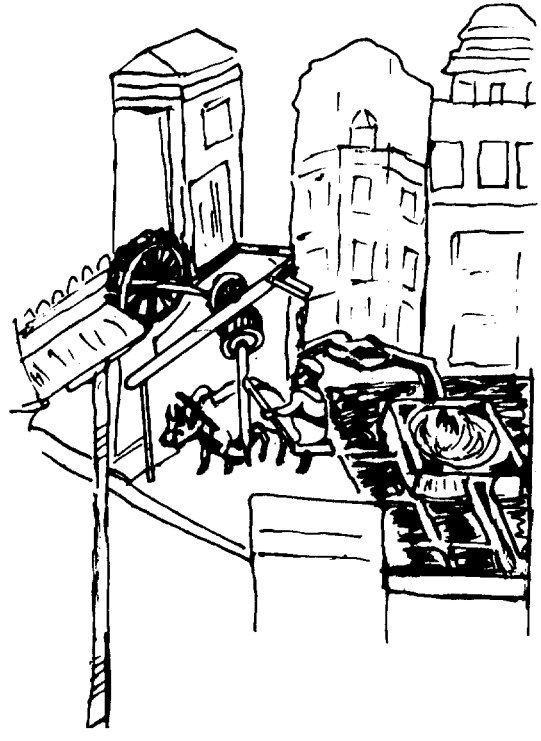


Fig. 4 (b) From a Painting by Maddu *Chela*, f. 99b

from India by two routes, via Burma and Indo-China, in about the fifth century AD and, via Central Asia, in the thirteenth. This would mean that the cotton-gin must have been in use in India before the sixth century; but for this, when Needham was writing, there was no evidence at all.

The device being technologically significant — "the most ancient form of rolling mill," in Needham's words — it was particularly important to test this hypothesis. Schlingloff[26] did well to identify the scene in an Ajanta

Fig. 5 : Cotton Gin depicted in Ajanta Cave I, *ca.* 600.

[26] D. Schlingloff, "Cotton Manufacture in Ancient India," *Journal of the Economic and Social History of the Orient*, 17.1 (1974) 81-90, esp. 89-90.

painting on "the left wall of Cave I to the left of the second cell-door"[27] as one of cotton-processing activities. But "the rectangular frame... the upper part of which is a double string [*rect.* roller]" cannot possibly be a scutching bow, as believed by Schlingloff.[28] Ishrat Alam has rightly identified it with the Indian cotton gin: the rollers are thin, because, for lack of a crank-handle, the upper roller had to be rotated by hand.[29] (See Fig. 5). Thus we have the geared cotton-gin well attested for the sixth century, in conformity with Needham's hypothesis. It was not yet the instrument identical with that of later days, since it had no crank-handle; and we must suppose that this was possibly one reason why, when China received it, it was divested of its worm-gear and given two crank-handles, or a handle and a pedal, to rotate the two rollers.

This raises the question of the coming of the crank to India. The Ajanta cotton-gin confirms the fact that ancient India was not in possession of this device. Unluckily, the great interest in the reason for its late appearance, shown by Lynn White[30] and Needham,[31] has yet to inspire research on it in India. The earliest occurrence of the cranked well-hoist in Europe has not been dated to earlier than 1425, while in China "the regular right-angled variety" appeared as early as the thirteenth century (*Science and Civilisation*, IV(2), pp.116). The crank-and-piston were also located by Needham in an eleventh-century Chinese painting.[32] For the Indian cotton-

---

[27] G. Yazdani, *Ajanta: the Colour and Monochrome Reproductions of the Ajanta Frescoes, Based on Photography*, London, 1930, Part I, Plate XII.

[28] Schlingloff, op. cit., p.90.

[29] Ishrat Alam, "Textile Tools as Depicted in Ajanta and Mughal Paintings" in: Aniruddha Ray and S. K. Bagchi (eds), *Technology in Ancient and Medieval India*, Delhi, 1986, pp. 130-31. This, of course, compels a revision of the argument advanced by John Daniels and Christian Daniels, "The Origin of the Sugarcane Roller Mill," *Technology and Culture*, 29.3(1988) 506, that the two-roller cotton gin in India "evolved relatively late, somewhere around 1100," and also of their conclusion (*contra* Needham) that there is an unresolved "question of a European versus an Indian origin" (p. 508).

[30] Lynn White Jr., *Medieval Technology and Social Change*, pp. 107-10.

[31] J. Needham, *Clerks and Craftsmen in China and the West*, 1970, p. 186 & n.

[32] Ibid.

gin to work best, a full right-angled crank handle (and not just an elongation of one of the rollers outside the frame) is required, as can be seen in Needham's own illustration of two Sinhalese specimens (*Science and Civilisation*, IV(2), Plate CLVII (Figs 417 & 418, opp. p.122). (See also Fig. 6.)

Unless one holds that the crank originated in India, of which there is no proof (no illustration of it is traceable in ancient Indian painting and sculpture), it must follow that its diffusion in India is a medieval, post-thirteenth-century phenomenon. The likely source is, naturally, China, rather than Europe, and the likely route, Central Asia. There is no Indian illustration of the crank earlier than the seventeenth century, when it

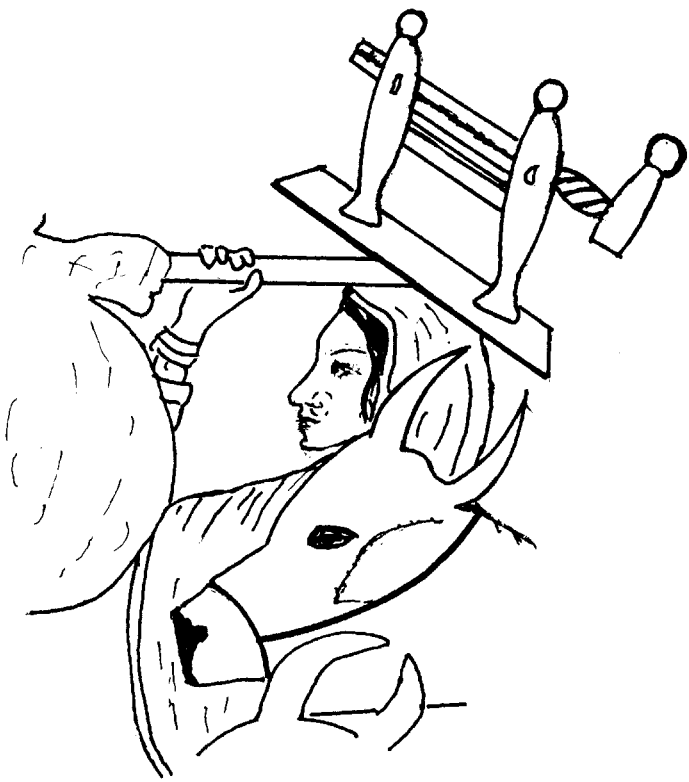


Fig. 6 : Cotton gin with crank handle, Kangra school c. 1750, National Museum, New Delhi. It is possible that the painter has mistakenly transferred the worm to the handle (where it has no function to perform) from the two rollers projecting on theother side.

appears in paintings of the spinning wheel, e.g. Bichitr's "Blind Singers"[33] and a painting (showing a woman spinning) of Aurangzeb's time.[34] It is, however, clearest in a mid-eighteenth-century Kangra painting showing the cotton gin (Fig. 6).[35] The crank would seem to have spread gradually, finding its natural place in various existing devices, over the four centuries, the fourteenth to the seventeenth. Though its progress was possibly slow, the efficiency it imparted to each instrument in which it was incorporated must have been very considerable.

THE SCUTCH-BOW

As in the case of the cotton-gin, so in the case of the cotton-carder's bow, Needham's attribution of its origin to India has been confirmed by research. Earlier, the scientific perception, as presented by R. J. Forbes, was that the bow was present in pre-historic Bronze-Age Europe for separating wool-fibres, that it inexplicably disappeared in the classical age, and then reappeared in Europe in the fifteenth century.[36] In a 1969 address I pursued Arabic dictionary definitions to show that "bowing" first appears only in the *Qāmūs* of al-Fīrūzābādī, *ca.* 1366-67.[37] I was later able to trace an eleventh-century reference to the device in Persian poetry.[38] Needham was rather brief on the device, stating that it came to China "with cotton itself", which event could be either that of the sixth century or of the thirteenth; but he added, almost intuitively, that "this was probably an Indian

[33] For a reproduction of the painting (Victoria and Albert Museum, London, IM-27-1925), see Ivan Stchoukine, *Le Peinture Indienne a l'Epoques des Grands Moghols*, Paris, 1929, Plate XLV.

[34] For a reproduction in F. R. Martin, *The Miniature Painting and Painters of Persia, India and Turkey*, London, 1912, II, Plate 207(a).

[35] Original in National Museum, New Delhi. See S. P. Verma, *India at Work*, Aligarh, 1994, Plate XV.

[36] R. J. Forbes, *Studies in Ancient Technology*, IV, Leiden, 1956, pp. 11, 26.

[37] Irfan Habib, "Technological Changes and Society, Thirteenth and Fourteenth Centuries," reprinted in Debiprasad Chottopadhyaya (ed), *Studies in the History of Science in India*, New Delhi, 1982, II, pp. 824-5.

[38] Irfan Habib, "Medieval Technology: Exchanges between India and the Islamic World," *Aligarh Journal of Oriental Studies*, 2(1985)197-222, esp. 216.

technique" (*Science and Civilisation*, IV(2), p.127). In 1969 I had ventured to contest this supposition.[39] I was soon proved wrong, however, by Schlingloff's quotations of reference to the scutch-bow in the *Jātakas* and in the *Milindapañho*, texts that must go back to the early centuries of the Christian era. He also cited Hemacandra's *Abhidhānacintāmaṇi*, written in the twelfth century.[40] It is tempting to postulate a slow diffusion of the scutch-bow from India sometime after the Arab conquest of Sind (early eighth century), to Iran and Central Asia (by the eleventh century), and, thence, on the one side, to China (thirteenth century), and, on the other, to the Arab World (fourteenth century) and Western Europe (early fifteenth century).[41] Whatever one may think of these detials, the essential hypothesis of Needham stands vindicated.

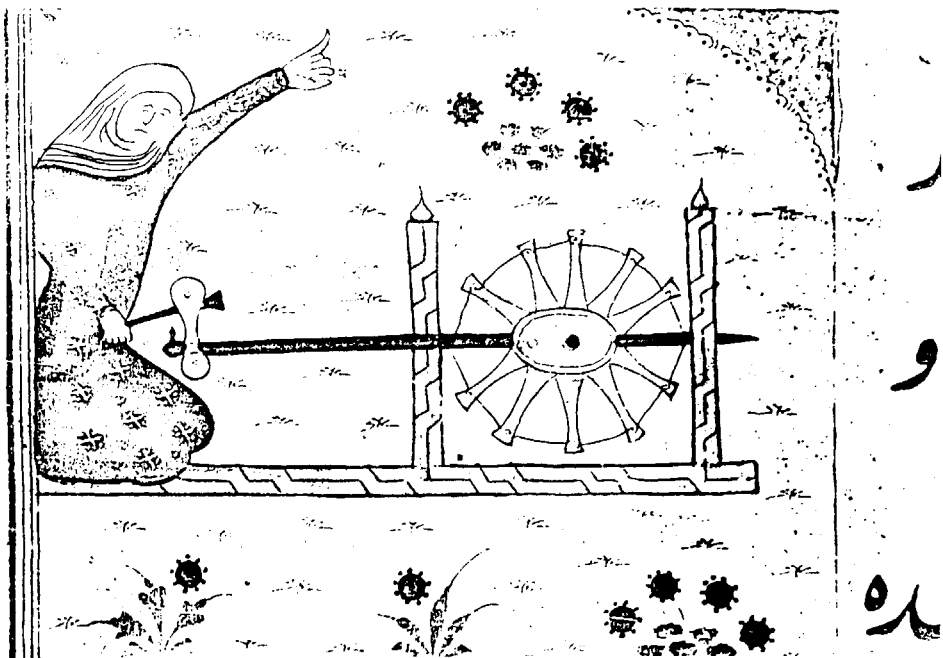


Fig. 7: Earliest Depiction of Spinning Wheel in India : Maḥmūd Shādīābādī, *Miftāhu'l Fuzalā*, British Library MS Or. 3299, f. 94b. 1468-69 AD.

---

[39] *Studies in the History of Science in India*, op. cit., II, p. 825.

[40] Schlingloff, op. cit., pp. 86 & n., 88.

[41] Cf. Irfan Habib, "Medieval Technology: Exchanges between India and the Islamic World," op. cit., pp. 216-17.

SPINNING WHEEL

The spinning wheel is an instrument seemingly so indigenous to India, that historians of science had unanimously assumed it to be of Indian origin, and had looked for its dates of invention at either about 500 BC or 750 AD.[42] Lynn White Jr. in 1960 was the first to contest this assumption;[43] and Needham in *Science and Civilisation*, IV(2), p. 108, upheld Lynn White on this, from "the evidence at our disposal." In fact, up till now, no description or depiction of this most interesting instrument, combining the belt-drive with the fly-wheel, has turned up from India earlier than 1350 AD, when 'Iṣāmī offers the first definite evidence for it, while the first illustration of the spinning wheel is no earlier than 1469 (Fig. 7). In Persian poetry of Iran, the references to women using the wheel go back to Anwarī, *ca.* 1138-39.[44] In the Arab World the first possible description is in Ibn Miskawayh (eleventh century) and a fairly clear depiction has been found in a Baghdad MS of 1237.[45] The first indication of the presence of the spinning wheel in Europe, on the other hand, does not go beyond *ca.* 1200 with the mention of wheel-spun yarn at Speyer.[46] This is so late, when compared with dates of the spinning wheel's occurrence in the Iranian and Arab zones, that Needham's objection to Lynn White's thesis about the spinning wheel's European origin[47] (*Science and Civilisation*, IV(2), p. 103), seems well taken, even without our looking at the Chinese evidence. Needham was indeed able to show that the spinning wheel has a much earlier history in China, with a clear depiction of it from the eleventh century.[48] In *Science and*

---

[42] See, for example, R. J. Forbes, *Studies in Ancient Technology*, IV, Leiden, 1956, pp. 155-6; he provides no references for his statements.

[43] Lynn White Jr., "Tibet, India and Malaya as Sources of Western Medieval Technology," *American Historical Review*, 65 (1960) 517-18.

[44] Cf. I. Habib, "Medieval Technology: Exchanges, etc," op. cit., pp. 203-4, for the references to sources for spinning wheel in India and Iran.

[45] Cf. Ahmad Y. Al-Hassan and D. R. Hill, *Islamic Technology, an Illustrated History*, Cambridge/Paris, 1986, pp. 185-86.

[46] Lynn White Jr., *Medieval Technology and Social Change*, p. 119.

[47] Cf. Lynn White Jr., "Tibet, India and Malaya as Sources of Western Medieval Technology," op. cit., p. 517.

[48] J. Needham, *Clerks and Craftsmen*, p.186n. and Plate XX (Fig.47).

Civilisation, IV(2), pp. 105-7, he traces the quilling wheel, the precursor of the spinning wheel in China, to the beginning of the Christian era; and researches of Chinese scholars have traced the spinning wheel itself to that early period in China.[49]

With Needham's basic thesis on the spinning wheel so well vindicated, we are now enabled better to see how it was diffused from China, entering the Islamic world (by the eleventh or twelfth century), and passing on to Europe and India in the thirteenth and fourteenth centuries. Why it took so much time for the world to learn from China is another question.

DISTILLATION

In Vol. V(4) of *Science and Civilisation*, especially pages 85-6,97,104-7 and 131-2, Needham offers a fundamental reconstruction of the history of liquor distillation in India, and, by its reconstruction, has forced a review of the theory prevalent until recently that the production of alcohol originated in the Mediterranean world in the thirteenth century.[50] Needham shows much respect for Mehdihassan, who had in many papers drawn attention to possible evidence of early liquor-distillation in India; and he had, of course, before him Ray's *History of Hindu Chemistry*,[51] with its citations of early medieval texts on distillation. None of this, even the linguistic curiosity inherent in the double meaning of *sunḍa* (elephant's trunk, side tube), gave any certainty of India's role in the early history of alcohol production. But Needham carefully analysed the archaeological evidence of stills from Taxila, first brought to light by Marshall and A. Ghosh,[52] now

---

[49] Gao Hanyu and Shi Bokui in *Ancient China's Technology and Science*, Beijing, 1983, pp. 505-8.

[50] Cf. A. C. Crombie, *Medieval and Early Modern Science*, New York, 1959, I, pp. 134 - 37; R. J. Forbes, *A Short History of the Art of Distillation*, Leiden, 1970, pp. 57-55, & c.

[51] P. C. Ray, *History of Hindu Chemistry*, Calcutta, 1902; revised edition, *History of Chemistry in Ancient and Medieval India*, Calcutta, 1956.

[52] Needham cites Marshall, *Taxila*, Cambridge, 1951, I, pp. 140, & c., and Plate 125 (Nos.127-129a), as well as A. Ghosh, "Taxila (Sirkup), 1944-45," *Ancient India*, No.4, pp. 41-82. The description of the still by A. Ghosh is on p. 64 (not p. 63 as in Needham's reference) and the "condenser" is figured (no.73) on p. 65, in *Ancient India*, No. 4.

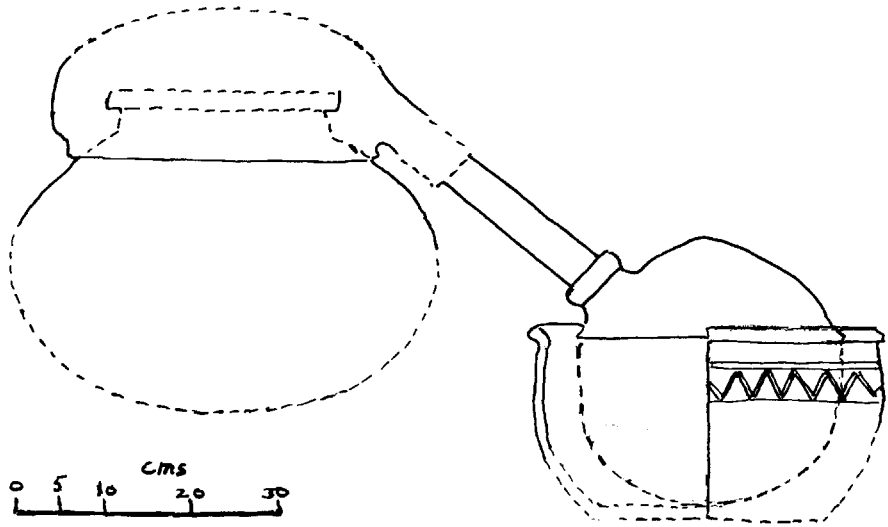


Fig. 8 : R. F. Allchin's Reconstruction of the Shaikhan Dheri (Charsadda) Still, 1st Century BC - 2nd Century AD (*South Asian Archaeology - 1977*, ed. M. Taddei, p. 773).

heavily reinforced by Raymond Allchin with numerous remains of stills from the Shaikhan Dheri (Charsadda, NWFP, Pakistan) excavations.[53] (See Fig. 8). Needham gave these stills the name of "Gandhara stills", compared them with the western or Hellenistic type of his still-classification, and then propounded that they were essentially "retorts" and, because of their early date (150 BC-150 AD), they might well be "the origin of all such forms of still" (pp. 85-6). The pottery remains at Shaikhan Dheri were so extensive, viz. one alembic, 130 receivers, and many possible still-bodies ("with soot on them"), and the receivers so capacious, that one must assume alcohol (not, for example, mercury) to be the intended product. This would give precedence to India over all other countries in liquor distillation.

---

[53] When Needham wrote on distillation for Vol.V(4) of his *Science and Civilisation*, F. R. Allchin's paper "Evidence of Early Distillation at Shaikhan Dheri" was still unpublished, but it actually anticipated Needham's vol. (1980) in print, appearing in *South Asian Archaeology, 1977*, ed. Maurizio Taddei, Naples, 1979, II, pp. 755-97.

Needham's discussion does not, however make clear what degree of success the Gandhāra stills could obtain in producing pure alcohol. It could have given only a heavily diluted alcohol, and, if the fire was kept low, to reduce dilution, the pace of collection must have been very slow.

The modifications that were introduced in Italy in the twelfth century (possibly in close exchange of ideas with the Arab world, as some terms tend to show) were designed to improve cooling so as to increase pure alcohol collection at a low level of heat. The "Moore's head" had a water-container set over a spoon-like alembic, a concave roof and annular rim-collection, connected by a tube with the receiver. This undoubtedly led to the achievement of a much higher degree of purity in the distilled alcohol than under any other device. There is a possibility, that, travelling through the Islamic world, the new stills would have soon reached India. The fresh wave of alcohol extraction, then, which India seems to have witnessed by the late thirteenth century, probably obtained its impetus from the improved stills now received. (For this new popularity of liquor distillation, the evidence from Ziyā Baranī (1357) has been discussed by me elsewhere,[54] and need not be laid out afresh.)

It is true that by this time there were alternative forms of stills also available, as Needham shows: these are what he calls the "Mongol still" (condensation in a catch-bowl within the still) and the "Chinese still" (with the catch-bowl connected by the side-tube with receiver outside), the former depicted on the wall of a cave of the period 1031-1227, and the latter shown in a drawing of 1163 in China (*Science and Civilisation*, V(4), pp. 62-68, 78-79). But neither of these devices could have probably competed successfully with the improved stills from the Mediterranean.

The famous passage of *ca.* 1595 in the *Ā'īn-i Akbarī* of Abū'l Fazl,[55] in

---

[54] Irfan Habib, "Medieval Technology: Exchanges, etc.," op. cit., pp. 207-10. Ziyā Baranī's references to the stills (*bhaṭṭis*) and distilled (*chakānūda*) wine occur in his *Tārīkh-i Fīroz-shāhī*, ed. Saiyid Ahmad Khan, W. Nassau Lees and Kabir al-Din, Bib. Ind., Calcutta, 1862, pp. 156, 285, and refer to the reigns, respectively, of Kaiqubād (1286-89) and 'Alā'uddīn Khaljī (1296-1316).

[55] Abū'l Fazl, *Ā'īn-i Akbarī*, ed. H. Blochmann, Bib. Ind., Calcutta, 1867-77, I, pp. 76-77; translated by H. Blochmann, I, revised and ed. D.C. Phillott, Calcutta, 1927 & 1939, pp. 73-74. Elsewhere (text p. 95; tr., p. 86), Abū'l Fazl describes the still for distillation of aloe-wood.

which three kinds of liquor-stills are described, is examined by Needham (pp. 106-7), from Blochmann's translation; and he identifies the three kinds respectively as the Mongol, the Chinese and the Hellenistic types. But while one may let pass the identification of the first still as "Mongol", the second is clearly Gandhāran. Abū'l Fazl expressly states that the condenser was the receiver itself placed in cold water. The third, which Needham identifies as "Hellenistic" is still more interesting, since it clearly has the Moore's head (water at the top and still-head shaped like a "spoon", so expressly described). It was, in other words, the medieval Italian-Arab still. (See Fig. 9).

Needham observes that it was the Gandhāra still, which some time between the seventh and twelfth centuries, was recognized as more practical than the Mongol and Chinese types and "adopted accordingly" (p. 80).

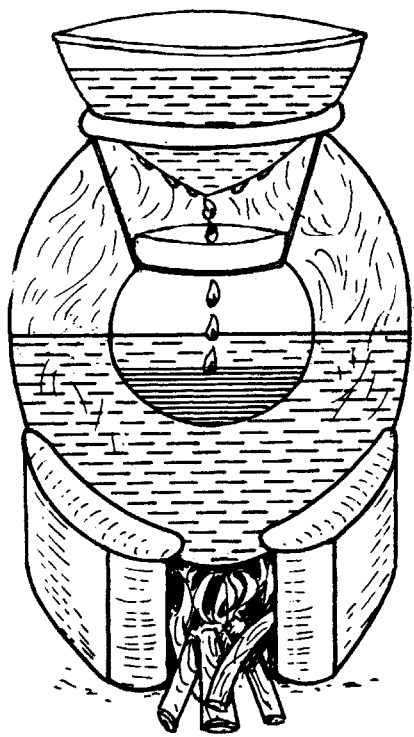
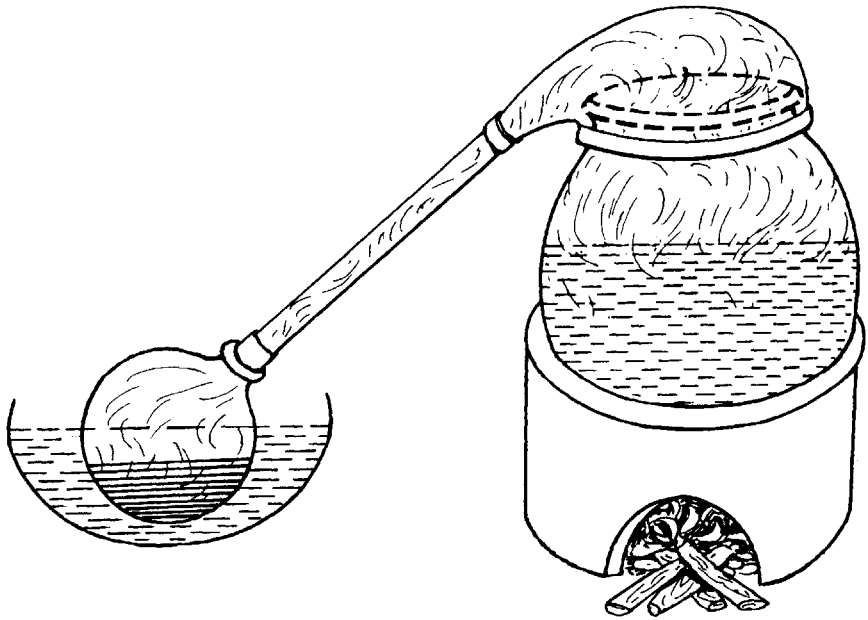


Fig. 9 : Stills reconstructed from Abū'l Fazl's description in the *Ā'n-i Akbarī*, ca. 1595.
(a) Still of the 'Mongol' type



(b) Still of the 'Gandhāra' Type

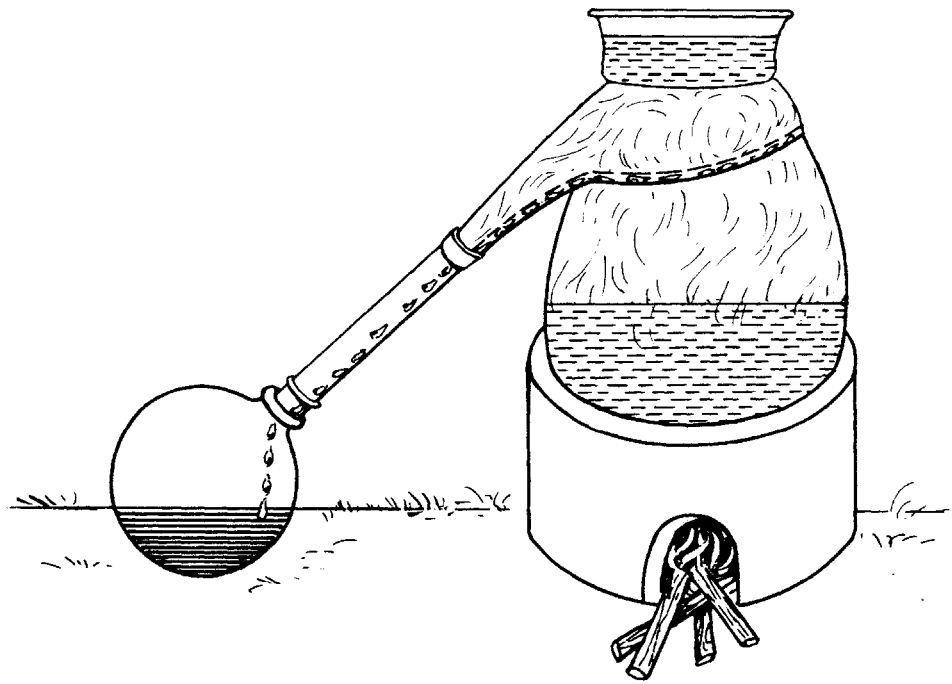


Fig. 9 (c) : Still of the Arab-Italian Type

But clearly, it was still not as efficient as the medieval Mediterranean still, which the *Ā'īn-i Akbarī* clearly describes; and which, as we have just speculated above, might well have already arrived here in the thirteenth century.

ZINC

On the history of zinc before its separation was achieved in Europe by Henekel in 1721, there has been much speculation. The earlier achievement of zinc-isolation outside Europe was attribued by Ainslie to China, and Hommel to India; and B. Laufer, who gives these references, pleads rather weakly for Persia.[56] Needham's researches (*Science and Civilisation*, V(2), pp. 213-15) resulted in his obtaining very early dates for separated zinc in China, as he pursued it back from Sung Ying Hsing's "classic account" of its distillation from calamine (1637 AD). "We can be sure," he concluded, with reference to China, "of the existence and use of isolated zinc metal from 900 [AD] onwards" (p. 214).[57]

Needham promised to investigate the beginning of zinc smelting in India in Sec. 36 of his work (V(2), p.254); but death prevented him from providing us the results of his investigations. There are some suggestions of the antiquity of the process in India. Ray assigned Nāgārjuna, the author of *Rasaratnākara*, to the seventh or eighth century, and this text describes the extraction of zinc, "the essence of calamine";[58] but Keith doubts such an early dating of the text.[59] Indeed, Sana Ullah noted that brass was

---

[56] Berthold Laufer, *Sino-Iranica: Chinese Contributions to the History of Civilisation in Ancient Iran*, Chicago, 1919, pp. 214-15.

[57] Writing on metallurgy in *Ancient China's Technology and Science*, Beijing, 1983, p. 403, He Tangkun does not show as much confidence in so early a date for zinc-smelting in China. While he dates the deliberate addition of zinc oxides to copper, in order to produce brass, to the period of the Western Han (206 BC-24 AD), he assigns to the Ming dynasty (1368-1644) the first production of "metallic zinc" in China.

[58] Ray, *History of Hindu Chemistry*, I, p. 49, quoted by Sana Ullah in J. Marshall, *Taxila*, II, p. 571.

[59] A. B. Keith, *History of Sanskrit Literature*, London, 1920, p. 512.

recognized as an alloy of copper and zinc only in the sixteenth century in India.[60] Abū'l Fazl (*ca.* 1595) in a rather neglected passage, notes that "*jast* (zinc), which to some is the essence of calamine, and is close to lead, is not noticed in scientific works; in India it is mined at Zawar in the territories of Ajmer."[61] Much depends therefore, on when zinc began to be separated at Zawar; and it was a welcome move to undertake a proper archaeological exploration of the mines. In the early announcement of the results of the excavation under K. T. M. Hegde, it was claimed that radiocarbon dates of 170 ± 60 BC and 30 ± 50 AD had been obtained for "the zinc ore mining and smelting industry"; "nearly intact structural remains of the furnaces used in the destillation of zinc in antiquity" were stated to have been actually found.[62] These conclusions received considerable publicity, but seem now to be in need of modification. From a report by P. T. Cradock, one learns that the first-century AD and earlier dates apparently related only to silver mining, which thereafter ceased. "Zinc production by distillation" seems to have begun only by the fourteenth century AD, continuing until the early nineteenth century.[63] This would suggest that zinc-separation in India came distinctly later than in China, given the evidence presented by Needham. One cannot at present also be sure whether the discovery of the process in India was influenced by rumour or information from China, or was a totally independent one.

DECIMAL NOTATION

Two of the few occasions where Needham seems to me to be pleading a special case are when he argues that China, not India, was the ultimate source of machines for perpetual motion, and of the modern system of decimal notation. On the first claim, made in *Science and Civilisation*, IV(2),

---

[60] Marshall, *Taxila*, p. 571.

[61] *Ā'īn-ī Akbarī*, ed. Blochmann, Bib. Ind., I, p. 35.

[62] *Indian Archaeology, 1983-84, a Review*, Archaeological Survey of India, New Delhi, p. 77.

[63] See P. T. Cradock's report on carbon dates from the Zawar area in *Radiocarbon*, 38 (1994) p.109.

pp. 532-46, S. R. Sarma has already written a definitive piece;[64] and I need not say anything more on it.

The second claim has, to my knowledge, not been examined as closely in the light of the Indian evidence. Needham argues in *Sciene and Civilisation*, III, pp. 5-15, that the Indian shift to decimal notation and place-value arithmetic derived (through South-East Asia) from China, which, according to him, had possessed, long before the third century AD, "a fundamentally decimal place-value system." While Needham has traced the rudiments of the place-value system to numbers found in the Chinese oracle-bone inscriptions of the second millennium BC, he inexplicably ignores the fairly early Indian literary evidence. The concept of zero occurs in Piṅgala (pre-200 BC), and a clear reference to the place-value system (the world population being said to occupy twenty-nine notational places) has been found in the Jaina text *Anuyogadvāra* (assigned to *ca.* 100 BC). The zero is explicit and the place-value system implicit in Āryabhaṭa I's arithmetic(AD 499). Both palce-value (with numbers in words) and zero occur in Varāhamihira's *Pañcasiddhāntikā* (*ca.* 550); and Subandhu (ca. 600) clearly defines zero.[65] Clearly, this theoretical tradition was independent of any Chinese influence; and it is reasonable to suppose that it would have ultimately found reflection in the actual writing of numbers.

The Chinese connection Needham conjectures to lie in the Sanskrit/ Sanskritic inscriptions of South-East Asia which apprear to carry numbers with place-value earlier than in India: Cambodia has one of Śaka 526 (= 604 AD), Champa of Śaka 609 (= 687 AD), Java of Śaka 654 (= 732 AD). Zero occurs in inscriptions of Śaka 605 (= 683 AD) and Śaka 608 (= 686 AD).[66] Inscriptions found in India containing such numbers have often

---

[64] Sreeramula Rajeswara Sarma, "Perpetual Motion Machines and their Design in Ancient India," *Physis: rivista internationale di storia della scienza*, NS, 29.3. (1992) 665-76.

[65] The information in this paragraph is drawn from S. R. Sarma, "Śūnya, Mathematical Aspect" in: Bettina Bäumer (ed), *Kalātattvakośa: a Lexicon of Fundamental Concepts of the Indian Arts*, Delhi/New Delhi, 1992, pp. 400-05.

[66] The inscriptions are dated in the Śaka era, with its epoch in 78 AD. The epoch of 128 AD mentioned by Needham (III, p. 11n.), has never been applied to the Śaka era, but is one of the epochs postulated for the era used by the Great Kushanas. The only epoch used for the Śaka era in inscriptions and by astronomers has been that of 78 AD.

been held to be later, as may be seen from the lists compiled by Fleet and by Datta and Singh.[67] What Mirashi holds to be the first indisputably genuine Indian inscription containing place-value figures is dated Śaka 701(779-80 AD),[68] and the zero appears first only in an eighth-century plate. Only in the ninth century do decimal numbers become universal in Indian inscriptions. Needham therefore supposes that though South-East Asia used forms of Indian numerals, the place-value system was Chinese in inspiration, and that contacts with South-East Asia then brought this style to India with a gap of a hundred or two hundred years after it had been in use in South-East Asia.

Much depends, then, on the Mankani plates from Gujarat dated to 346, written with decimal notation: the year, being in the Kalachuri era, corresponds to 594-5 or 595-6 AD. While publishing this inscription, Mirashi pronounced it "spurious", not on terminological or palaeographic grounds, but for the reason largely that it has a date too early for decimal notation![69] Mirashi himself notes G. S. Gai's reading of dates of two inscriptions given in the Vikrama era in decimal notation, viz., VS 699 (= 641 AD) and VS 794 (= 736 AD); his sole objection is that there had been earlier other readings of these dates, viz., VS 879 (= 821 AD) and VS 749(= 691 AD) respectively. If Gai's reading is correct, as is probably the case, the Mankani plates would no longer stand alone. There is also the Hatun inscription in Gilgit (Jammu and Kashmir), dated in the year 47 of an unknown area, with decimal placement of numerals, assigned on palaeographic grounds to "the seventh century, perhaps even earlier."[70] It is, therefore, likely that

---

[67] J. F. Fleet, *Corpus Inscriptionum Indicarum*, III, p. 209n.; B. Datta and A. N. Singh, *The History of Hindu Mathematics — a Source Book*, Bombay, 1962, pp. 40-43.

[68] V. V. Mirashi, "Nagardhan Plates of Svamiraja," *Epigraphia Indica*, XXVIII, p. 3. (Mirashi here pronounces as spurious the Tivarkhed plates whose date 553 Śaka /AD 631 is "recorded in decimal figures"). Fleet, op. cit., p. 209, quoting *Indian Antiquary*, X, pp.108 ff., lists the Samaugad grant of Dantidurga, "in the Dekkan," dated Śaka 675 (753-54 AD), among inscriptions carrying decimal notation. This is some twenty-five years earlier than Karkaraja Rashtrakuta's Dhulia grant of Śaka 701, considered the earliest known such inscription in Maharashtra.

[69] V. V. Mirashi, *Corpus Inscriptionum Indicarum*, IV: *Inscriptions in the Kalachuri-Chedi Era*, Pt.1, Ootacamund, 1955, pp. 160-63.

[70] N. P. Chakravarti in *Epigraphia Indica*, XXX, pp. 226-27.

the appearance of decimal-place numerals in India and South-East Asia was practically simultaneous; and this would take away much of the force from Needham's argument of a Chinese influence here.

There are two further points to note. Needham recognizes (III, p.11n.) that the "earliest zero symbol used in computation, the dot (*bindu*), occurs in the Bakshali MS", but he cites scholarly opinions dating it to the tenth century. This late date must be revised in view of Hayashi's detailed study of the manuscript. He "tentatively" proposes the seventh century as the period to which the manuscript should be assigned.[71] If so, even in zero, South-East Asia would lose its precedence, and, with it, any possibility of Chinese influence would become even more tenuous.

Even more significant is Needham's own reference to a Chinese text, *Khai-Yuan Chan Ching* of 718 AD, which, in its Chapter 10, described "the similar [i.e. decimal] Indian method of expressing numbers" (*Science and Civilisation*, III, p.12*n.*). True, this work might have exercised "little or no influence" on Chinese representation of numbers, but it does make it certain that in India, the decimal notation had been established at least about the beginning of the seventh centursy — a minimum margin of a hundred years before transmission to China would surely be reasonable. This simple fact makes it almost impossible that the Indian system of writing numbers with decimal placement was received from China through South-East Asia. It must on present evidence then, be deemed to be of independent origin.

I close with a disagreement with Needham, but not with any lessened sense of gratitude. Even from this seemingly miscellaneous assemblage of technological themes from Indian history touched upon by Needham, it is possible to recognize how much Indian history has gained from him. Even where he muses and speculates, or hazards a guess, that further research may not sustain, he makes us explore aspects of our past, which we would not have done had he not provided us with a source of inspiration and challenge. China alone does not have reason to be appreciative of what he has done: India too has much to thank Needham for.

---

[71] Takao Hayashi, *The Bakhshālī Manuscript, An ancient Indian Mathematical Treatise*, Groningen, 1995, pp. 148-50.