the endless screw or worm. This was unsatisfactory, but explainable because the treatise in which he did it[a] was concerned only with the lifting of weights.[b] Other early classifications were Indian.[c] In the +7th century Daṇḍin enumerated six types, among which were mobile, stationary, water-works, heat-engines, and mixed devices. Prince Bhōja,[d] about +1050, in his *Samarāṅganā-sūtradhāra*, distinguished between the principle (e.g. rotary or otherwise), the material, the purpose and the form of a machine (*yantra*). His list of merits of a machine is interesting; they included (*a*) proportionateness, (*b*) elegance, (*c*) efficiency for the effect intended, (*d*) lightness, firmness or hardness as the case might be, (*e*) noiselessness when noise was not wanted, (*f*) avoidance of looseness and stiffness, (*g*) smoothness and rhythm in motion, (*h*) controllability in starting and stopping, (*i*) durability. Other classifications could be collected from Arabic sources (though we have met with none in Chinese), but before the Renaissance there were no really analytical treatments of the subject.

Willis (1) divided all machines into classes according to whether the directional relation and the velocity ratio were constant or varying.[e] In each of the three main classes he considered rolling contact, sliding contact, wrapping connection, link-work, and reduplication. Thus in the first class (that where the directional relation and the velocity ratio are both constant), gear-wheels, bevel-wheels, worms, and the rack and pinion would be examples of rolling contact; cams and slots would show sliding contact; pulleys, belts and chain-drives would show wrapping connection; cranks, levers and rods would show link-work; and multiple pulleys or tackle would show reduplication. It is hardly necessary for our purpose to embark on an elaborate classification, and I propose to deal with the machine elements under the following heads: (*a*) levers, hinges and linkwork, (*b*) wheels, gear-wheels, pedals and paddles, (*c*) pulleys, driving-belts and chain-drives, (*d*) crank and eccentric motion, (*e*) screws, worms and helicoidal vanes, (*f*) springs and spring mechanisms, (*g*) conduits, pipes and siphons, (*h*) valves, bellows, pumps and fans.

Reuleaux (1) was probably right in his view that the chief criterion of gradual mechanical perfection was the completeness of the constraint of motion. Excessive play must have been the chief devil in all primitive machines, yet with the materials, tooling and lubricants available there was no other way of making them go round at all. Moreover, Reuleaux pointed out that a very important element in mechanical improvement lay in the substitution of 'pair-closure' or 'chain-closure' for 'force-closure'. An example of the latter would be the resting of a heavy rotary grindstone simply by gravity on bearings with no upper component to keep the axle in place under all

[a] Tr. Carra de Vaux (1), from the Arabic version of Qusṭā ibn Lūqā.

[b] The famous definition of Marx (pt. IV, xiii, 1; Paul ed. p. 393) was also partial, since it conceived of every machine as necessarily involving a tool for the production of commodities. This may be true in the broadest sense, if knowledge be included among them.

[c] Cf. Raghavan (1).

[d] He was the ruler of Dhār (Malwa) from +1018 to +1060; see V. Smith (1), p. 189.

[e] Directional relation is constant if while one mechanical component moves in a certain direction, the other also perseveres in its own direction (e.g. a pair of gear-wheels). It varies in such cases as the rocking motion of a saw, or the beam of an early steam-engine. The constancy of the velocity ratio is of course independent of any changes which the actual velocities of the two components may undergo during a given time, for they change at the same rate.

possible circumstances, or the holding of a lathe-tool against the work by the muscular force of the operator. These are certainly the kinds of concepts which would have to be applied in the assessment of engineering achievement in any culture.

(1) Levers, Hinges and Linkwork

Of the lever and its great early application the balance something has already been said in the physics Section (Vol. 4, pt. 1, pp. 22 ff.). There we saw that the Mohist engineers in the −3rd century must have been acquainted with most if not all of the equilibrium principles stated by Archimedes. In the immediately following centuries, this understanding of the lever was put to good use in China in the making, almost on a mass-production scale, of crossbow triggers (*nu chi*[1]). These mechanisms, which involved intricate bent levers and catches, were beautiful and delicate bronze castings, and deserve the full description which they will receive below in Section 30 on military technology.[a] On a scale much larger, and with the use of timber, the lever had also been employed from an earlier date in the swape, *shādūf*, or counterweighted bailer bucket (*chieh kao*[2]), which again will be discussed in connection with water-handling machinery (p. 331 below). Lever-presses[b] (beam-presses) were not dominant in China, though the trip-hammer constituted an important application,[c] and heavy loads tended to be hoisted by combinations of levers rather than by pulley tackle.[d] But the most elaborate use of levers in early times in China was undoubtedly in textile machinery, where levers and connecting rods were united with treadles to form complicated linkworks. Evidence which will be presented in the appropriate place (Sect. 31 below) shows that the Chinese were far ahead of the West in loom construction—in the −1st century, for example, if not the −4th, they already had the essentials of the draw-loom (*hua chi*[3]) before Europe or perhaps any other civilisation had advanced from the primitive vertical-warp loom to the horizontal-warp loom with its harness of heddles. This precocity is perhaps symbolised by the fact that the Chinese word for loom, *chi*,[4] implies that it is the machine *par excellence*.[e]

The assembly of such a linkwork, however, involves the use of hinges or movable joints. Essentially the hinge (*chiao*[5]) is a pin (*chiao ting*[6]) and two hooks (*kou*[7]), and both these structures were readily available in all antique civilisations.[f] For doors or windows the pin tended to be long and the 'leaves' (the Chinese used the same term *ho yeh*[8]) broad and flat;[g] for links in rods the pin would be short and the hook-tails

[a] We have already had in the seismograph (Vol. 3, pp. 628 ff.) an instance of complex link and crank motion, at least if the reconstruction of Wang Chen-To (1) be accepted. In any case his discussion of the level of this technique in ancient China is very relevant here.

[b] Beck (1), p. 79; Usher (1), 1st ed. pp. 76, 77. See further pp. 209 ff. below.

[c] Cf. pp. 183, 390 below.

[d] Cf. p. 99 below.

[e] For an appreciation of the role of linkwork in modern machinery see Jones & Horton (1), vol. 1, pp. 391 ff., 418 ff.; vol. 2, pp. 385 ff.; vol. 3, pp. 109 ff., 162 ff., 200 ff., 240 ff.

[f] Sirén (1), vol. 1, pl. 78, gives photographs of a number of Chou specimens.

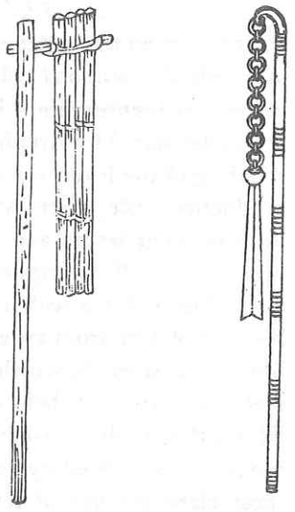
[g] Modern traditional examples are described in Hommel (1), pp. 292, 300. For ornamented flat bronze plate hinges of early Chou time see White (3), pl. LXXXIX, or Thang Lan (1), pl. 58, fig. 4. The latter album also illustrates some beautiful hollow-casing bronze hinges of the Warring States period

[1] 弩機 [2] 桔槔 [3] 花機 [4] 機 [5] 鉸 [6] 鉸釘 [7] 鉤 [8] 合頁

elongated. Relevant in this connection are the curious bronze hooks on the ends of poles which White (1) described from the Loyang tombs of the −6th century; these seem to have been used for setting up easily dismountable booths or tents.[a] Yuan[b] and Ming[c] books discuss the ancient names for hinges, notably *chin phu*,[1] saying that this was the pin, and that the cylindrical sockets were called *huan niu*[2].[d] One ancient name for the whole hinge was the 'knee-bender', *chhü hsi*[3] or *chhü hsü*.[4]

There were prominent uses of links in agriculture and war as well as in textile technology: first the link-flail (cf. below, Sect. 41) called *lien chia*[5,e] (Fig. 374 *a*) and the war-flail (Fig. 374 *b*); and secondly the component parts of the efficient horse harness (the postillion or chest-trace harness), which though not connected at their junctions by pins (being of leather), nevertheless performed the office of a linkwork system (cf. below, p. 304). This harness was in full use at the beginning of the Han period, that is to say, some ten centuries at least before Europe possessed an efficient harness for horses.

Perhaps more characteristic of European ideas of Chinese civilisation was the collapsible umbrella or parasol (*san*[6,7]), working by means of the sliding levers still familiar in everyday use. While sun-shades were common in Greek and Roman daily life, and certainly go back to Babylonian times, they were not generally collapsible.[f] We have, however, an indication that the principle of the later collapsible Chinese parasol was used in +21, for in that year Wang Mang had a very large one made as a magic baldachin (*hua kai*[8]) for a ceremonial four-wheeled carriage.[g] The mechanism is said to have been a secret one (*pi chi*[9]), and the +2nd-century commentator, Fu



(*a*) (*b*)

Fig. 374. Flails as examples of linkwork and chain connection. (*a*) Farmer's flail from the *Nung Shu* of +1313. (*b*) Iron war-flail from the *Wu Ching Tsung Yao* of +1044. One of the names for the latter, the 'iron crane bird's knee' (*thieh ho hsi*), came to be used as a technical term in +11th-century mechanical engineering for all kinds of combinations of rods and chains in linkwork (cf. p. 461 below).

(pl. 64, fig. 4). Early Han examples are drawn in Kao Chih-Hsi & Liu Lien-Yin (*1*), p. 651. Certain vessels also had hinges in the Chou and Han. In the museums at Nanking and Canton one can find bronze wine-kettles with hinges excellently made both on the lid and on the birdbeak-shaped spout. Fig. 375 shows an example of a link-hinge from the −10th century.

[a] Thang Lan (*1*), pl. 63, fig. 3, shows a bronze central canopy holder of Warring States time with free rings surrounding a central boss.

[b] E.g. the *Cho Kêng Lu*. [c] E.g. the *Shan Thang Ssu Khao* and the *Liu Chhing Jih Chai*.

[d] *Niu* is a knot or button, and the point is that on Chinese garments the button-hole was never *in* the stuff, but formed by looping a silk cord which projected *from* the stuff.

[e] Alternatively, *chia*[10] and *lien chieh*.[11]

[f] Aristophanes, however, has a reference in the *Knights* which might imply collapsibility (Feldhaus (1), col. 945). But it has been suggested that the familiar lever system we use now was a Chinese invention which came to the West later (Feldhaus (2), pp. 45, 46).

[g] *Chhien Han Shu*, ch. 99C, p. 15*b*, tr. Dubs (2), vol. 3, p. 413; *TPYL*, ch. 702, p. 7*a* (Pfizmaier (91), p. 288).

[1] 金鋪 [2] 環紐 [3] 屈膝 [4] 屈戌 [5] 連枷 [6] 傘
[7] 繖 [8] 華蓋 [9] 秘機 [10] 架 [11] 撻稍

Fig. 375. Link-hinge on a bronze wine-kettle (*ho*) of the −10th century, self-dated by an inscription naming the Chou High King Mu (photo. CPCRA and BCFA, cf. Thang Lan (*1*), pl. 28). Height 11 in., diameter of mouth 7½ in. From Phu-tu Tshun, Shensi, cf. Watson (1), p. 24, pl. 69.

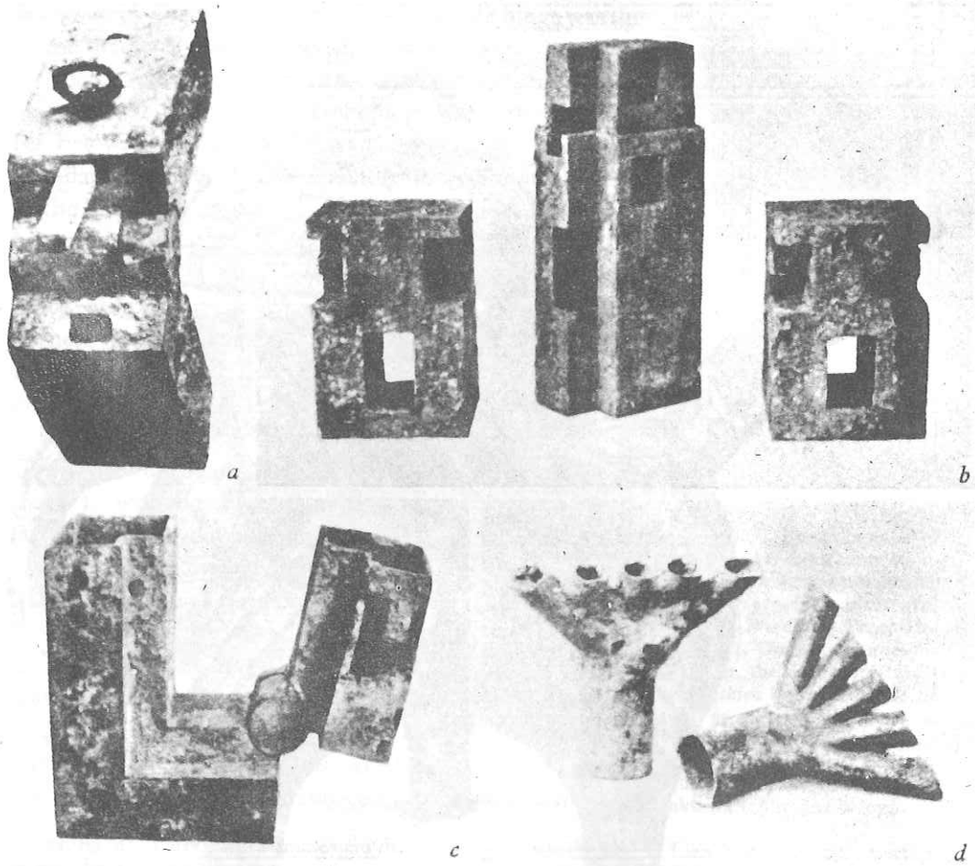


Fig. 376. Bronze castings of complex design from the −6th century (Chou period) excavated at Loyang (White, 1). (*a*) Bronze socketed hinge with locking slide-bolt (pl. 13); (*b*) bronze rebated socketed couplers with holes for tenons and stanchion pins, some using the principle of the bayonet catch (pl. 34); (*c*) bronze rebated hinged corner-fitting socketed to hold wooden members (pl. 11). Cast bronze tubular connecting-joints for assembling the rods or canes of ancient Chinese carriage canopies (Thang Lan, *1*); (*d*) two six-way branching holders of the −4th century (pl. 64, fig. 2).

Chhien, adds that his umbrellas all had bendable joints enabling them to be extended or retracted.[a] Collapsible umbrella stays of Wang Mang's time, or shortly after it, have actually been recovered from the tomb of Wang Kuang at Korean Lo-Lang, and are illustrated by Harada & Komai.[b] But the system must go back much earlier, for similar objects of Chou date (−6th century) from Loyang are figured by White.[c] Other pieces of bronze which White described[d] are beautiful castings of very complex design (Fig. 376 *b*). He calls them 'socketed couplers', though at first sight they look like locks. Bulling (4, 7, 8) believes that some of the designs on the backs of Chou and Han bronze mirrors can only be understood as flattened representations of ceremonial umbrella tops,[e] but her view has not won much support. In any case, after all this, one is hardly surprised, though the discovery is pleasing, to find collapsible umbrellas exactly like those of modern China in the woodcuts of a book printed about +1270 which deals with divination but contains many scenes of daily life.[f]

The question of origins is more interesting than it might appear, for towards the end of the Later Han period, about +160, the folding chair or stool became popular in China.[g] As we shall see later on, it was known first as the *hu chhuang*[1] (barbarian bed), and certainly came from the West, probably from Greek Bactria. But the evidence just given shows that it cannot have been responsible for the appearance of pivoted rods and linkwork in Chinese technology.

Mastery of the art of collapsibility achieved some remarkable successes in the Yuan period which are referred to in a curious entry in the *Shan Chü Hsin Hua* (New Discourses from the Mountain Cabin). Yang Yü tells us that

> a lacquer worker of Suchow named Wang, in the Chih-Chêng reign-period (+1341 onwards) made a boat of ox-hide, covered inside and out with lacquer. It was dismountable into parts, and was brought to Shangtu (the Manchurian summer capital of the Yuan emperors), where

[a] *Chhi kang chieh yu chhü hsi, kho shang hsia chhü shen yeh.*[2]

[b] (1), vol. 2, pls. XIX, XX.

[c] (1), pls. XIV, XVII. This gives a little colour to the old tradition that the inventor of the collapsible umbrella was Yün shih,[3] the semi-legendary wife of the celebrated −5th-century artisan Kungshu Phan (cf. Li Nien (*27*), p. 2).

[d] (1), pls. XI, XIII, XXXIV. Some of these have built-in slide-bolts which have to be released before the hinge can open. This is perhaps the place to mention the cast bronze tubular connecting-joints used for assembling the rods or canes of ancient Chinese carriage canopies (cf. Fig. 376*d*). At the Chêngchow Archaeological Institute in 1958 I greatly admired some six-way examples of these from the Chhu princely tomb of the Warring States period recently excavated near Hsiao-liu-chuang. Four- and five-way connections for as many ribs are even more numerous in museums. A special paper has been devoted to these interesting objects by Chhang Wên-Chai (*2*). By the San Kuo period (+3rd century) they were being made of iron, a rather intricate casting job (see Anon. *16*). Cf. Anon. (*17*), pl. 27. The simpler forms of these tubular junctions (three- and many four-way cruciform pieces) appear also in the steppe cultures, as may be seen from the remarkable work of Gallus & Horváth (1) on the pre-Scythic peoples of Hungary, e.g. pls. LII, LIV, LIX, LX. For a similar Hallstatt example see Kossack (1), fig. 3. The junctions in these cultures may well have been parts of horse-gear rather than chariots or carriages.

[e] Naturally a cosmic significance of ceremonial umbrellas is not far to seek; in Sect. 20*d* the ancient and widely held theory of the heavenly dome (Kai Thien) was described. If the emperor corresponded to the pole-star, no ornament could have been more appropriate for him than a symbolical umbrella. In the *Chou Li* this symbolism is explicit (cf. Biot (1), vol. 2, pp. 475, 488).

[f] *Yen Chhin Tou Shu San Shih Hsiang Shu* (see p. 143 below), ch. 2, pp. 5*b*, 12*a*, 14*a*, 24*b* and 29*b*. Cf. Yang Jen-Khai & Tung Yen-Ming (*1*), vol. 1, pls. 4, 7, 11.

[g] See Stone (1); Ecke (2).

[1] 胡床 [2] 其杠皆有屈膝可上下屈伸也 [3] 雲氏