

DRAGONS AND TOADS. THE CHINESE SEISMOSCOPE OF A.D. 132

by

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Abstract. The Chinese seismoscope of A.D. 132 is generally considered one of the outstanding inventions of its time. No attempt to reconstruct the mechanism from the brief description in its inventor's biography has fully followed the specifications found there. In particular, although the extreme sensitivity of the device is emphasized, no modern reconstruction has been capable of detecting tremors too weak to be noticed without any mechanical help at all. This essay considers the mechanical principles that would make high sensitivity possible within the conditions imposed by the text. A reconstructed instrument of the sensitivity specified in the source can result only from a program of systematic experimentation. The design proposed (one of several that might fit the description) is sensitive enough to serve as a starting point for such research. It also incorporates for the first time in a Western language recent archeological discoveries that bear on mechanical and esthetic aspects of the seismoscope.

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John Milne, writing in Japan a century ago his germinal scientific study of earth movements, asserted that "the earliest seismoscope of which we find any historical record is one which owes its origin to a Chinese called Chôko. It was invented in the year A.D. 136" (Milne 1886: 13).¹ Milne proceeded to translate the text which recorded this invention, and to reconstruct the instrument that it described. This device, his translation made clear, incorporated a pendulum that released one of eight peripheral balls to signal not only the fact but also the direction of a distant earthquake.

Milne's translation was done via Japanese, as the transliteration of Chang Heng's

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¹Ink has been spilt now and then over the question of whether Chang's device ought to be called a seismograph. Milne, who has generally been given credit for first recording the invention of the seismograph, set down the basic distinction. It still stands, and there is no room for contention in it (note particularly the words we have italicized): "To construct an instrument which at the time of an earthquake shall move and leave a record of its motion, there is but little difficulty. Contrivances of this order are called *seismoscopes*. If, however, we wish to know the period, extent, and direction of each of the vibrations which constitutes an earthquake, we have considerable difficulty. Instruments which will in this way measure or write down the earth's motions are called *seismometers* or *seismographs*" (1886: 13).

張衡 (78-139) name implies.² Many retranslations and re-reconstructions have followed, gradually providing a sounder understanding of the documents—for instance, it was soon recognized that the recorded date corresponds to A.D. 132, not 136—and proposing mechanical arrangements more likely to register earthquakes of less than devastating force at the point of observation—for instance, the greatly superior inverted pendulum incorporated in reconstructions by Hagiwara and Imamura in 1938 (Imamura 1939). All of these efforts have been surveyed and critically assessed twice in connection with further improvements, in 1959 by Joseph Needham and in 1963 by Wang Chen-to (who first studied Chang's seismoscope in 1936). Since no important new work has appeared since; their accounts of the last century's investigations remain authoritative.

Wang Chen-to's work over several decades has defined the problem: to design a machine that conforms to the textual description and that operates as the text asserts. This is a general problem with respect to ancient Chinese mechanisms, and never a simple one. The most obvious reason is that the recorded descriptions, while usually precise in some respects, are never full and are sometimes corrupt. Since claims made in texts about what a machine could do were always made by individuals in particular circumstances for particular reasons, there is always the possibility of exaggeration or fabrication. There exist, of course, many techniques for challenging the intactness or veracity of a historic document. The best studies of ancient mechanisms have drawn on these critical methods. At the same time, respecting the integrity of the documents, they have avoided freely 'improving' the text by emendation.

Wang, in his final papers, went a step further, providing a model for further studies by verifying the meaning of every technical term against Han dynasty linguistic usage, iconography, and technological practice. Learned in Han literature and well informed about recent archeological discoveries, he carried philological understanding of the text to a point that is unlikely soon to be bettered in any major respect. One of the aims of this essay is to make Wang's linguistic and iconographic interpretation of the text more widely accessible.

Our main aim is to carry further another aspect of reconstruction. Previous attempts have conformed closely to the words of the description, but would not operate as claimed. It is indeed difficult to believe that Chang's seismoscope was sensitive enough, as the Han history's account asserts, to detect a tremor centered hundreds of kilometers away that could not be felt in Loyang. It is therefore not surprising that the anecdote has usually been tacitly dismissed. Needham does not ignore it. He speaks of "the striking test of the delicacy of the instrument." He notes nevertheless that in an instrument reconstructed in Tokyo, only exceptionally was the initial longitudinal wave encountered in experiments strong enough to release the ball in the correct direction, although observers had clearly felt the tremor; the subsequent transverse waves usually released balls at right angles to the direction of the main shock when balls were released at all (1959: 630). Ima-

²Milne had been anticipated to some extent by the indefatigable translator August Pfizmaier (1871: 148), who published in German a shorter derivative account from the Sung encyclopedia *T'ai-p'ing yü lan*, 752: 1b.

mura's model, based on a toppling inverted pendulum, required a minimum acceleration of 8.7 gals to be activated (1939: 39). This acceleration is equivalent to an earthquake in which people flee their houses for safety, although structural damage is not extensive (Sieberg 1923: 428). One may well doubt the utility of a device that can only signal tremors the observers themselves feel, and cannot reliably indicate direction.

We do not believe that the specification of high sensitivity can be more blithely disregarded than any of the other particulars in the historical account. In what follows we will attempt to demonstrate that by following the language of the text exactly and conforming to the limits of techniques feasible in the Western Han period, one can construct a seismoscope of requisite sensitivity. In order to attain this sensitivity our design differs from Wang's in several respects, some of them not unimportant where there are gaps of information in the old description; but we do not differ from his literal understanding of the surviving description.

The Text

Here is our translation of the text from the biography of Chang Heng in *Hou Han shu* (59: 1909)³ followed by a few notes (keyed by superscripts) to explain points that have been responsible for confusion in previous translations:

陽嘉元年，復造候風地動儀。以精銅鑄成，員徑八尺，合蓋隆起，形似酒尊，飾以篆文山龜鳥獸之形。中有都柱，傍行八道，施關發機。外有八龍，首銜銅丸，下有蟾蜍，張口承之。^(一)其牙機巧制，皆隱在尊中，覆蓋周密無際。如有地動，尊則振龍機發吐丸，而蟾蜍銜之。振聲激揚，伺者因此覺知。雖一龍發機，而七首不動，尋其方面，乃知震之所在。驗之以事，合契若神。自書典所記，未之有也。嘗一龍機發而地不覺動，京師學者咸怪其無徵，後數日隕至，果地震隴西，於是皆服其妙。自此以後，乃令史官記地動所從方起。

In the epochal year of the Yang Excellence period (A.D. 132) he also [or again] made a 'wind-observing earthquake instrument.'^a It was cast of highly refined copper alloy [presumably bronze], round with a diameter of eight *ch'ih* (2.2m) and closed by a convex top. It resembled a wine-jar. It was decorated with characters in seal script, mountains, tortoises, birds, and animals.^b Within was a general pillar^c which, moving horizontally along eight roads, worked mechanism(s) which tripped trigger(s).^d Outside were eight dragons holding copper alloy balls in their mouths. Below were toads with their mouths wide open to receive them. The trigger mechanism(s) fitted completely inside the wine-jar, which was closed tightly by the cover so that there was no [visible] joint. When there was an earthquake the wine-jar would be shaken, a dragon's trigger would be released, and it would spit out a ball, which a toad would catch in its mouth. The sound [that resulted from the] shaking was rousing;^e those in charge of tending [the instrument] would thus be alerted. Although one dragon would trip its trigger, the [other] seven heads [or those of the other seven heads] would not move. By noting the direction

³Citations of the Standard Histories refer to the Chung Hwa Book Co. ed. of 1959-1977.

[that the ball and the actuated dragon] faced one would know the location of the earthquake. When tested against the phenomena [the results] tallied as though divine. As far back as the records reach there had been nothing [like it].

Once the trigger of one dragon tripped but no tremor was felt. The scholars of the capital all took it amiss that there was no confirmation. A few days later an imperial messenger arrived. In fact there had been an earthquake in Lung-hsi [Kansu]; thereupon they all admitted that [the seismoscope] was a wonder. From that time on, officials of the Astronomical Bureau [also responsible for recording seismic phenomena] were ordered to record the directions from which earthquakes originate.

Notes

a. *Hou feng ti tung i*. *Hou feng* was an established Han word for determining wind direction with a feathered streamer and perhaps also with a weathercock. The context (here and in the brief notice in *Hou Han shu*, 6: 260) does not make clear whether the longer term refers to a wind indicator and a seismoscope, or to one device that combines the two senses. The latter view has prevailed on the reasonable ground that, as Needham puts it, the apparatus "determined the azimuth direction in which the earthquake's epicentre lay, just as the weathercock determined the direction of the wind" (1959: 627 note a). We will suggest anon that the reference to determination of wind direction is more than analogical. It is interesting that, read literally, the text speaks ambiguously of the location of the earthquake rather than specifically of its direction; only the final sentence allows the meaning of "so *tsai* 所在" to be narrowed down. *Hou Han shu*, 6: 260, calls the instrument a "*hou feng ti tung t'ung i* 銅儀," not a significant variation.

b. *Shan kwei niao shou chih hsing*. Pelliot questioned the juxtaposition of mountain and tortoise coupled with that of birds and beasts (Moule 1924: 38). Wang studied these decorative themes in considerable detail to show that they often occurred together in the Han. He suggested that the seismoscope was ornamented with the sky-animals of the four cardinal points (*ssu ling* 四靈: black tortoise or tortoise and serpent for north, virid dragon for east, vermilion bird for south, white tiger for west) above a border of mountains representing earth as counterpart of sky (1963b: 15-16; 1963c: 21-22).

c. *Tu chu*. Although this term is not found in the scant surviving literature of Han architecture, Wang demonstrates through an examination of archeological evidence that it is consistent with the main load-bearing pillars of tombs and some residences, which extant texts usually call *chung chu* 中柱 or *t'ien chu* 天柱. Han stone and wood pillars were commonly either octagonal or round. Han tomb reliefs of bronze pillars that figure in pre-Han legends portray them as round (1963b: 7-11). We see no reason to rule out either possibility.

d. *Shih kuan fa chi*. No translation has reflected a precise understanding of this phrase. The words *kuan* and *fa*, because of their opposed verbal senses "close" and "open," have been interpreted as a compound. No such compound—neither *kuan-fa* nor *fa-kuan*—is attested in early Chinese. On the other hand, *fa chi* is used by Ts'ao Chih 曹植 (192-232) just past the end of the Han, and by later writers, to mean tripping a crossbow's trigger mechanism (called *ya chi* 牙機 in the Han, a

compound that occurs in this text).⁴ Since the seismoscope text speaks three times of “dragon triggers (*lung chi* 龍機),” it is clearly those that are being released (Wang 1963b: 13). *Shih kuan*, then, is also a verb-object construction, indicating by common senses of the two words a prior movement of a mechanism (*kuan*) that trips one or more “dragon triggers.”

e. *Chen sheng chi-yang*. Wang does not discuss this phrase, although it has never been translated closely or interpreted literally, and is, we will argue, important in understanding the mechanism. *Chi-yang* does not mean “high and loud” (Moule) or “sharp” (Needham), but consistently, from at least the Han, “rousing” (*Han shu*, 88:3605).

The sound is not simultaneous with the dropping of the ball. As Moule recognized, it was literally the sound of “shaking” (*chen*), a word that the historiographer had applied just previously to the wine-jar. We emphasize that the rousing sound is said to occur at a stage in the sequence *before* the “dragon trigger” is released, and all the more before the indicator ball drops into the toad’s mouth.

With these points in mind we will proceed to our interpretation of the text, then to our essay at reconstruction, and finally to some comparative remarks on the history of seismoscopes in Europe, both before and after the advent of the seismograph.

Interpretation of the Text

As we have pointed out, if the signal is to have any informative value, the instrument must react to either longitudinal or transverse waves, but not to both. The sensitivity of the instrument is thus a matter of concern. If it were sensitive enough to be activated by the first mild tremors (P-waves or *primae undae*) emitted in any earthquake of practical interest to the Han Chinese—i.e., those of sufficient magnitude to cause damage, and with epicenters up to about 3000 km away from Loyang—there would not have been much of a problem. Since the P-waves are longitudinal, the ball would have been dropped either by a dragon facing the epicenter or by one facing in the opposite direction.

The ambiguity of the signal in Imamura’s reconstruction must have been due to the insensitivity of the instrument. The most simple-minded but methodologically the least objectionable way to avoid this ambiguity is to take seriously the anecdote about the sensitivity of the instrument. To do so is to reopen to question the most basic aspects of the device’s functioning. In addition, the working of the crossbow trigger mechanism—which, as the terminology makes clear, served as the release mechanism for the copper balls—requires a clearer explanation than it has yet been given.

The “general pillar” and the “wind-observing earthquake instrument.” An earthquake indicator necessarily comprises some sort of pendulum, whether suspended and swinging or inverted and rocking. In order to indicate the range of devices possible within this constraint, the final section of this essay will discuss the history of seismoscopes in Europe.

⁴The term occurs in Ts’ao’s “*Ch’i ch’i* 七啟,” in *Wen hsuan* 文選 (Hui-wen-t’ang ed.), 34: 13a.

It must be emphasized that the text does not necessarily imply that the pillar is the pendulum. The pillar is only one of two objects which might have served this purpose; the second possibility is the bronze outer shell. The movement of the pillar "horizontally along eight roads" may refer to the movement during an earthquake of a pillar set in the earth, in which case the outer shell could have swung from the top of the pillar, a construction that would have presented little difficulty to Chinese technicians 1850 years ago. But one is not constrained, in identifying the pendulum, to choose between the pillar and the outer shell.

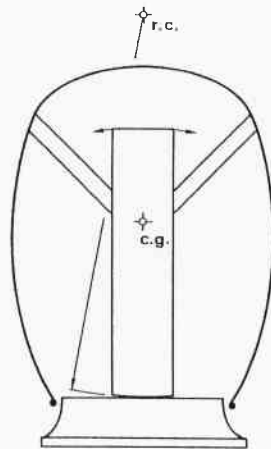


Figure 1
Principle of the inverted pendulum

It is conceivable that the outer shell was joined fast to the central pillar, of which the underside was rounded to allow it to rock. With this convex surface standing on a flat support, the whole of the pillar and bronze shell would then have acted as a massive, unitary inverted pendulum (the principle is diagrammed in Figure 1). One can demonstrate that such a construction would have been within reach of Han technicians.

Which of these alternatives best fits the description in the *Hou Han shu*? The epithet "wind-observing" provides a clue that the outer shell acted as, or was part of, a pendulum—that is, that the pendulum was not completely enclosed. If that were the case, a sensitive instrument of this design, set up in the open air, would be activated not only by earthquakes, but by winds. If its properties as a wind indicator were undesirable—and they would decisively interfere with its use as a seismoscope—it would have to be located indoors.

This suggests that either the second or third possibility approximates the specifications in the text. Having to choose between the two, we prefer to avoid the far-fetched assumption that when Chang Heng mentions the horizontal movement of the pillar, he refers to a ground movement that might not even be perceptible.

If the pillar formed a unit with the housing, as in the third alternative, the movement would be that of the joined pillar and shell relative to the ground. This version provides the most natural interpretation of the text. We will argue below that such a pendulum makes possible a seismoscope of the requisite sensitivity. The possible meaning of the "eight roads" that the text mentions will be discussed in connection with the reconstruction.

The "dragon triggers." Needham (1959: 628) sums up the need felt by every seismologist to have the instrument immobilized once a longitudinal tremor has caused a ball to be dropped, lest the transverse waves (S-waves), which follow on the P-waves, activate other "dragon triggers." There are two ways in which additional "dragon triggers" might have been activated. They might have been set off by the pendulum as it went on swinging, as it would have done in Wang Chen-to's first reconstruction. Imamura obviated this possibility by his toppling inverted pendulum. The second possibility is that vibrations in the instrument caused by the tremors themselves could have released the triggers if there were not some provision for locking them. This requirement could have been responsible for Imamura's version of the trigger design, and for a modification in Needham's discussion of 1959.

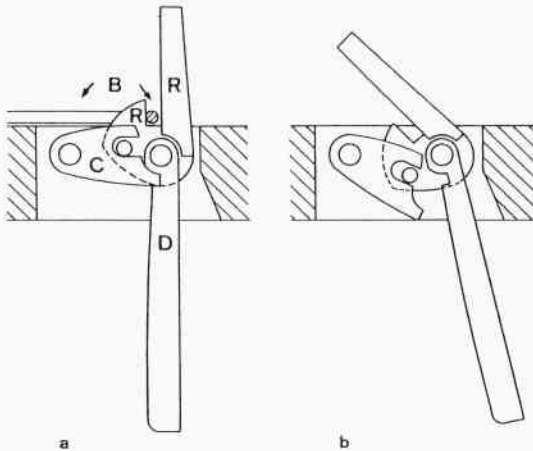


Figure 2
Han crossbow trigger

Ingenious *ad hoc* arrangements are not necessary to avoid the second danger. Those troubled by it have not noted that "ya chi" was, as we noted in the introduction, the normal Han term for the trip lever and cam mechanism of the crossbow trigger (Figure 2); the literal sense, "toothed mechanism," referred to the elongated, tapering trip lever.

The original crossbow trigger differed from releases designed *ad hoc* for previous reconstructions in that the release is locked against all forces except the one

exerted by the trigger; the only exception (in Wang Chen-to 1963c: Figs. 44-48) does not resemble the crossbow trigger mechanism in either function or form. The locking of the Han device made it extremely safe for its original purpose. If the triggers in the dragons' heads were of the same kind, no matter how violent the tremors following the one that dropped the indicator ball, only direct activation of another trigger would cause a second ball to be dropped.

If indeed the common Han mechanism were used, only when a trigger within the "wine-jar" housing had been activated would the jaws open; it would have been impossible to open them from the outside. How, then, could a ball dropped from the jaws of a dragon have been replaced? Conceivably there was a hole for this purpose in the dragon's head, or perhaps a hidden lever to activate the trigger from the outside. It is also possible that the replacement ball came from the inside.

The latter suggestion answers the question of what activated the trigger, a question that arises naturally once a toppling pendulum is eliminated as the direct agent. The simplest alternative is the spare ball, stored inside, and somehow released by the rocking of the pillar and shell.

Needham (1959: 630) remarks that the statement "the [other] seven heads would not move" implies that the activated one did move. The text is ambiguous on this point, since the subject of the verb is tacit; it could either have been seven heads or seven triggers that did not move. Immediately before this passage, the tripping of one of the triggers is mentioned; that movement may well have been meant. The text does not make the more obvious contrast between the seven dragon heads still carrying balls in their mouths and the one with a gaping mouth that all too clearly no longer held a ball. It is merely prudent, therefore, to evaluate the possibility that the ball in the activated dragon's mouth was immediately replaced from within. We suggest that this was the case. The convex cover on top, which has no other purpose, would have let someone open up the housing and insert a new spare metal ball. If we are correct that the spare ball set off the trigger, until a new one was provided—manually or automatically—no "dragon trigger" after the first could be activated, and no further ball could drop from the blocked jaws of the dragons.

The preliminary sound from the "shaking" of the "wine-jar" was also significant enough to deserve special mention by the historiographer. In the most recent reconstruction Wang does not mention it, and whether he considers it to come from the dropping of the ball or from the lever of the trip mechanism knocking against the inside of the shell is not clear (1963c: 18, Fig. 45; but in the alternative design of Figs. 54 and 58 there is no such lever).

Since the sound is plainly identified with the "shaking" that precedes the release of the trigger, we note that as the spare metal ball progresses downward within the seismoscope, a rousing sound could easily have been generated as the ball bounced against the shell before triggering the dragon's jaws. If the outer shell were joined to the pillar to constitute a rocking inverted pendulum, as we propose, it necessarily would have been open at the bottom. This would make it a most sonorous bell, the sound of which doubtless would have alerted the

attendants, who as we shall see had work to do.

The earthquake record. Two careful compilations of earthquake records from the standard histories and other familiar sources have been published in recent years. Both of them list, within a couple of decades after A.D. 132, two earthquakes of which the regions of catastrophe include Lung-hsi commandery (capital at present Lintao 臨洮, Gansu). The first, dated 1 March 138, is ruled out, since the record notes that it also caused considerable damage at the capital (the first compilation, Anonymous 1956: 441, nevertheless asserts that the anecdote refers to this event). The second record refers to a series of 180 shocks from November 143 to early 144 which caused great damage to the natural and manmade environment in a region roughly between longitude 104° and 106° east, and latitude 33° and 36° north, including Lung-hsi. The maximum intensity is estimated by the editors at 7 on the Richter scale (Anonymous 1970: 3-4, citing *Hou Han shu* 6: 260 and other less direct sources). The areas mentioned as damaged are distributed about a point in modern Gansu province roughly 700 km from Loyang. There is nothing in the record to cast doubt on the identification of this well-attested series of tremors with the story of the seismoscope's sensitivity. The anecdote would presumably refer to an early, severe shock in the series. The fact that the seism occurred about five years after Chang's death has no necessary bearing on its pertinence.

We have now outlined the deductions that we are able to make from the text. They carry us far toward a complete reconstruction. For the exterior appearance of the seismoscope, which the text describes in more detail than its interior, we follow Wang Chen-to's reconstruction in all except a few minor respects (1963c). We also draw on his studies of Han technology as they throw light on feasible interior mechanisms (1963b). In the next section we supplement the textual description and our direct deductions from it in order to propose a concrete reconstruction.

Reconstruction

The pendulum. We have outlined in the previous section an analysis of the text that leads us to believe that the central pillar and the bronze outer shell were firmly attached. This unit would have stood on the rounded end of the pillar. That rounded end need not have been spherical. Because no more than eight directions had to be indicated, it could have taken the form of eight sectors formed by the intersection of four cylindrical surfaces. The advantage of this configuration is that the oscillation is guided onto one of four planes, especially at larger amplitudes. Actually, of the sector surfaces no more need be shaped carefully than strips near the ribs formed by the intersections of the 45° surfaces. The arrangement is shown schematically in Figure 3. This configuration may explain the reference to "eight ways" in the text. An advantage of the strip configuration would have been that dust on the baseplate, which tends to interfere with operation, would have been crushed under these narrow but heavily loaded surfaces. The weight of the pendulum, assuming that the thickness of the bronze shell was 2 cm, would have been close to one metric ton. The energy stored in the wobbling pendulum would have been enhanced by concentrating most of the weight in the shell.

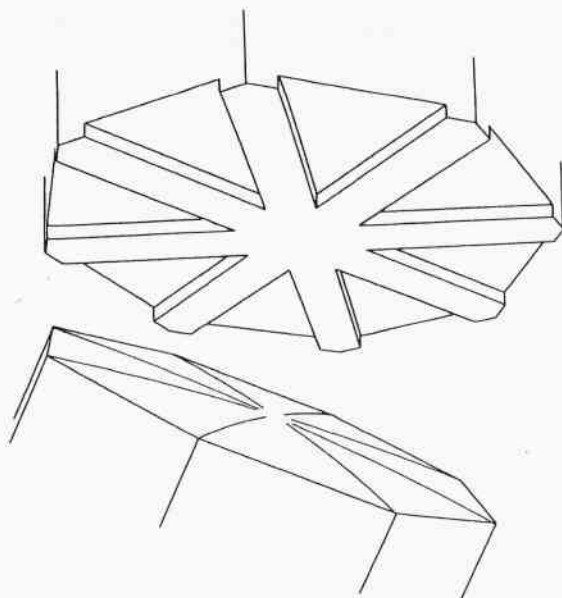


Figure 3
The "eight ways"

The central pillar may well have been octagonal in section, as sketched in Figure 3; Wang has shown that such pillars were common in the Han (1963b: 7-10). The flat sides of the pillar would have greatly simplified the mounting of the trigger mechanisms. Means of mounting practicable in the early second century A.D. would probably have dictated that the pillar be made of wood. If so, one would expect the lower end to be protected by a bronze cap which had been given the shape of eight cylindrical sectors suggested here, and its upper end to be capped by a piece of bronze dished out on top, as explained below.

The center of curvature of the bottom must be higher than the center of gravity if the pendulum is not to topple easily. If this radius is sufficiently large compared to the other dimensions of the inverted pendulum, the moment of inertia of the latter may be neglected. The effective pendulum length l would then be approximately equal to the difference between the radius of curvature and the height of the center of gravity. The period of oscillation is given by the formula

$$T=2\pi\sqrt{l/g}$$

in which g is the acceleration of gravity (ca. 9.8 m/sec²). If $l/g \approx 1 \text{ sec}^2$, i.e. if $l = \text{ca. } 10 \text{ m}$, a period of about 6 seconds results. This period is approximately in resonance with the most commonly occurring P-waves (Sieberg 1923: 140), leading the inverted pendulum to rock with increasing amplitude during an earthquake. The height of the center of gravity being roughly 1.5 to 2 m, the radius of curvature of the bronze pillar base would have been ca. 12 m.

It is not difficult to arrive at a qualitative idea of resonance by empirical observation of a not particularly systematic kind. Any earthquake of large magnitude

teaches the curious that certain walls rock back and forth with growing amplitude in the same rhythm as the seismic waves, while other walls of different dimensions are not affected. The notion of resonance as a function of length was well developed in the Han with respect to sound, as the work of Kenneth G. Robinson and others has long since made clear (Needham 1962: 184-202). Incorporation of resonant relationships in the design of the seismoscope, in a way that required nothing more than simple trial and error, would go a long way toward explaining the sensitivity implied by the description in the History of the Later Han.

A faraway earthquake, imperceptible at the capital but signalled by the seismoscope, does not tally with any previous reconstruction. The only study, to our knowledge, that has resulted in a model tested quantitatively for sensitivity was Imamura's. This model incorporated a central pillar with a heavy bob near its upper end (since it was meant to topple), standing on a flat surface of 3 cm diameter. The acceleration needed to overturn it is, as we have noted above, far greater than could result from an imperceptible seism. Reducing the minimum acceleration a single order of magnitude would reduce the diameter of the flat surface on which Imamura's pendulum stands to an impossibly small value. In other words, a simple inverted pendulum cannot be made sensitive enough to serve as the basis of a valid reconstruction.

This limitation of sensitivity does not rule out the inverted pendulum principle. It is possible that resonance figured in the release of the spare ball as well. We propose, as a simple example, that the latter was stored within the shell underneath the lid, on a concave metal dish with eight nicks at equal intervals along a raised rim, much like the dish that held mercury in de Hautefeuille's seismoscope (which we discuss below, p. 15). When an earthquake sets the inverted pendulum rocking, the metal ball would eventually pass over one of the eight nicks in the rim, activate a trigger, and roll into one of the dragons' mouths. The sensitivity of the instrument would be dramatically increased if the metal ball on the plate itself acts as a pendulum, rolling back and forth with a characteristic period in resonance with that of the pillar-shell unit. This resonance could have been attained if the periods of the two pendulums were equal or differed only slightly. Although the pendulums are mechanically coupled, their characteristic periods are independent. If they are chosen to be approximately equal, resonance will be the result.

A word must be said about the mechanics of coupled pendulums in resonance. The earthquake would first activate the inverted pendulum, which we call the primary pendulum, by imparting a certain amount of energy to it. Its rocking would activate the secondary pendulum, which consists of the metal ball on its plate. The mechanics of resonance implies that energy is slowly transferred to the secondary pendulum. The energy, if not dissipated, would continually be transferred back and forth between the two pendulums. In practice, friction always gradually diminishes the energy as it is transferred back and forth. If the masses of the two pendulums are different, for the same energy their maximum amplitudes are inversely proportional to the square roots of the masses. If the primary pendulum's mass is large relative to that of the secondary pendulum, as is the case

here, a small oscillation of the primary pendulum eventually causes a large oscillation in the secondary pendulum. Resonance, in other words, can be used to amplify the original small oscillation induced by the earthquake.

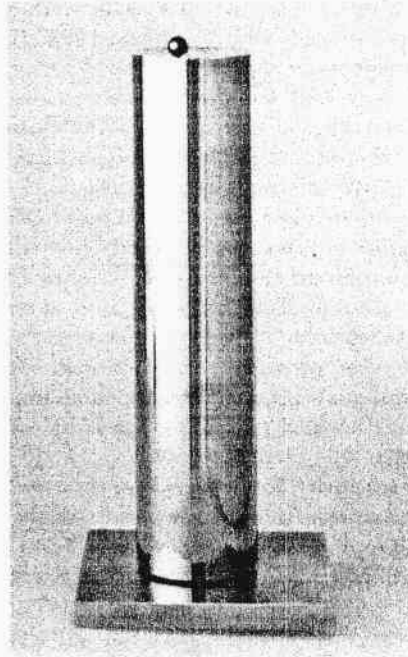


Figure 4
Model of a resonance pendulum

We have tested the application of this principle to a simplified model pendulum, consisting of a solid brass cylinder with convex and concave spherical ends (Figure 4). The cylinder weighed about 2 kg and had a diameter of 6 cm. It stood on its convex end, and a steel ball bearing was placed on its concave end. The radii were chosen (curvature of pillar base, 500 mm; radius of ball bearing, 6mm) so that the periods of oscillation were roughly equal. As a result the ball bearing rolling on the concave surface was in resonance with the rocking of the brass cylinder. The ball bearing, beginning at rest, rolled back and forth on top of the brass cylinder with increasing amplitude and finally spilled over the rim of the concave surface.

The idea of resonance between the rolling ball and the inverted pendulum may have evolved from a less sophisticated and less sensitive instrument in which the spare ball triggered one of the dragon heads. In such an instrument, the spare ball would have to be stored in a small depression above the central pillar, out of which it would have rolled when the oscillations of the pillar reached a critical magnitude. Shaping this depression experimentally to make resonance appreciable would have been an obvious next step to greatly enhance the sensitivity of the

seismoscope. Of course, in the absence of information about precursors or prototypes of Chang Heng's very sensitive instrument we cannot present this development as anything more than speculation.

The crucial question is whether Chang could have invented and made a seismoscope that depended on resonance in the ways outlined above. We believe that he could have done both. In the later Han period the equivalent of today's East Asian iron frying pan, the wok (*kuo* 鍋), was used under the name of *fu* 釜. The everyday use of such a roughly spherical sector, in which a ball or marble could have been rolled back and forth, would make its employment in studies of pendulum behavior nothing extraordinary. Moreover, the fact that these cooking utensils were made of metal renders it plausible that the rounded lower end of the pillar might have been shaped in iron or bronze.

The dragon triggers. We now turn our attention to the trigger mechanism activating the dragons' heads. We first briefly review the action of the Chinese crossbow mechanism (Figure 2). The trigger consists of three parts. The detent D and the release R for the bowstring B turn independently about a common pivot. The catch C turns around a second pivot unless its tongue is engaged by the groove in the detent. The hook on the release behind which the bowstring is retained is furnished with a deep notch within which the nock of the arrow fits directly against the bowstring.

When the detent is pulled, the catch is free to rotate, liberating the release. Since the catch acts as a lever, the detent requires less force to operate than would otherwise be needed. The long protruding arm of the release is a handle by which the trigger mechanism is reset after an arrow has been shot. The locking action of the trigger mechanism depends on the fact that the tongue of the catch, when engaged by the groove in the detent, can exert on the latter only a force which points in a direction passing through the center of rotation of D.

The shape of these parts, but not their basic configuration, has to be modified to adapt the trigger mechanism for use in the seismoscope, in which the resetting must be automatic. In the crossbow, this operation is done by hand. It consists of two manipulations: turning the handle clockwise to reset the release, and rotating the catch counterclockwise to reengage its tongue in the groove of the detent as the latter is simultaneously moved clockwise. Thus the state of Figure 2a is restored.

We carried out a number of trials on various trigger models modified from the crossbow mechanism. Making the release turn back automatically was not difficult. We ultimately gave the release R the form of an approximately horizontal lever, atop which a ball could roll. One end of it constituted the dragon's lower jaw, which held the ball in place against a fixed upper jaw. The weight of the ball was partly counterbalanced by a weight at the other side of the fulcrum of the lever. The lever, as soon as it had released a ball from the dragon's mouth by slightly turning downward, was turned back by the counterweight.

Providing for the automatic reengagement of detent and catch was so troublesome that we finally modified the device slightly by engaging detent D and catch C permanently. That necessitated transferring the locking action to the catch

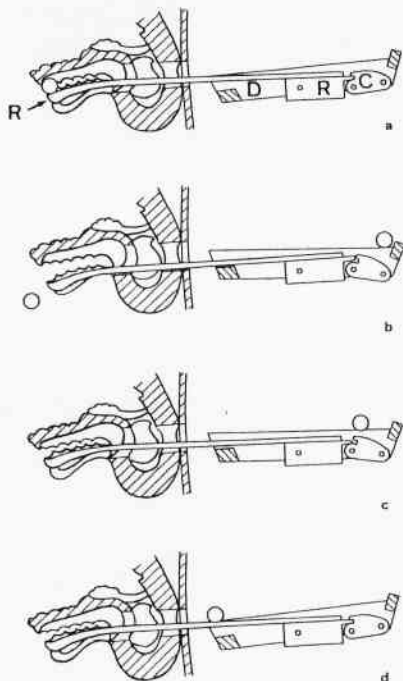


Figure 5
"Dragon trigger" mechanism

and the release R, which are momentarily disengaged when the system is triggered. Because in the Han device the release is always reset before the detent and the catch, this change was minor and easily made.

The release rotates about the same axis as the detent. The former is counter-weighted in such a manner that when there is a ball in the corresponding dragon's mouth the release rotates to the left when no longer held by the catch, but when there is no ball in the dragon's mouth it rotates to the right upon release. The catch rotates about a fixed axle at left, and is rotated by a second loose-fitting axle on the detent at right. The catch multiplies the slight rotations of the detent, ensuring reliable operation of the whole mechanism, which functions as shown in the sequence of drawings.

The model seismoscope trigger system which resulted is shown in Figure 5. Initially, in this model the catch holds the release, and the weight of the detent points it downward to the left (Figure 5a). The detent is activated by the spare ball dropping on it. The slight rotation of the detent thus caused lets the catch rotate through a larger arc, liberating the pawl on the release (Figure 5b). The release rotates downward, so that the ball in the dragon's mouth is free to drop. As soon as the ball clears the release, the latter rotates back and closes the jaw. In the meantime, the spare ball has begun rolling down the track atop the detent

toward its fulcrum (Figure 5c). Once the original ball has dropped, the detent, which is also counterweighted, rotates back, and with it the catch. The latter engages the release and blocks it until the detent has been activated again (Figure 5d). The spare ball eventually rolls from the track on the detent to that on the release, and finally comes to rest between the dragon's jaws. A working model of this mechanism performs flawlessly.

This reconstruction is of course not the only modification of a Han crossbow trigger that would fit the constraints of the problem, but it is as simple a change as we can conceive. We do not believe that a less speculative modification is possible within the limits of the historic data.

Exterior. We accept Wang Chen-to's reconstruction, with the following modifications dictated by our design for the mechanism:

1. The outer shell is joined to and suspended from the pillar. This feature is invisible, but it implies that the shell does not touch the pedestal on which the rounded end of the pillar stands.

2. the lid on top is smaller than in Wang's version, since it merely gives access to the secondary pendulum.

3. the dragons have been given a shape that allows the spare balls to descend through their necks, and the release of the trigger device to include the lower jaws. This shape, like that proposed by Wang, is consistent with Han design.

This exterior is shown in Figure 6. We reproduce it from Wang's last study in order to show our indebtedness to him for matters of exterior design (1963c: 13). Our own conception of the exterior differs from his only in the shape of the lid, the gap between the base and the shell, and the lack of taper in the latter (Han wine-jars did not ordinarily taper, but had more or less parallel sides). These differences may be seen in Figure 7, which depicts in cross-section our reconstruction of the interior. In it the path followed by the spare ball through the seismoscope is visible. The top of the pendulum is conceived as an eight-sided block of bronze which continues the wooden pillar and is concave at the top (see above, p. 10). After having spilled from the shallow dish underneath the lid into one of eight channels, the ball bounces against the outer shell before continuing on its zigzag way downward toward the trigger. This impact accounts for the rousing sound mentioned in the text, needed to alert attendants to place a new spare ball underneath the lid. Finally the ball already in motion drops on the detent of one of the dragon triggers. As a result, the dragon's head drops its ball, which is immediately replaced by the ball that originally triggered its release. Once a new ball has been placed in the dish atop the column, the apparatus is ready to detect a new tremor.

The Seismoscope in Europe

The oldest known seismoscope in Europe was invented by the abbé de Hautefeuille in 1703 (Sieberg 1923: 428ff). Its essential element was a flat bowl completely filled with mercury (see Figure 8a from Sieberg). The rim of the bowl was provided with equally spaced overflow gates. The mercury overflowing during an earthquake was captured in one or more beakers underneath the overflow gates (usually at least in two opposite beakers). The instrument fulfilled the same

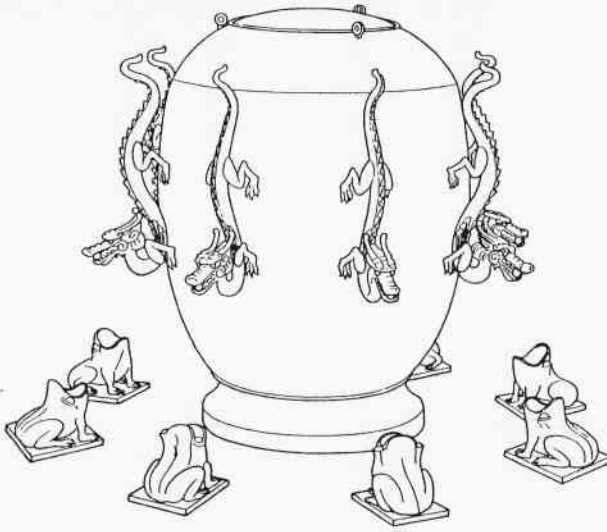


Figure 6
Exterior of the reconstructed seismoscope, from Wang Chen-to

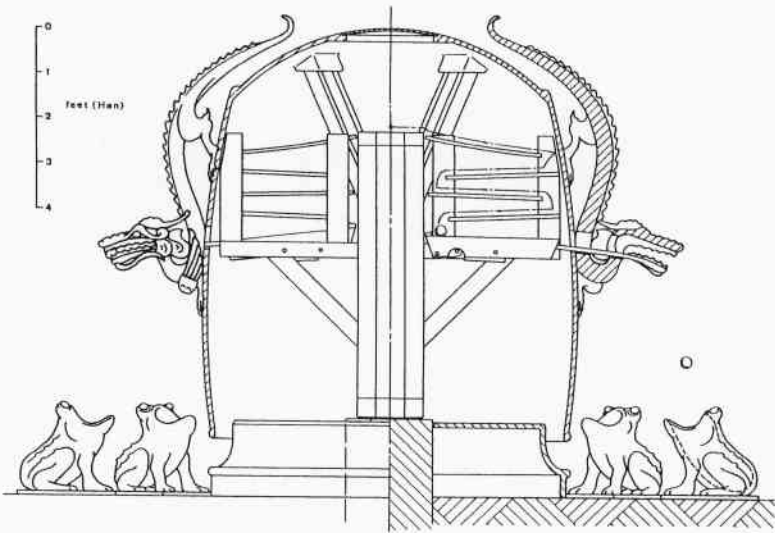


Figure 7
Cross-section of the Chang Heng seismoscope.
The path of the ball is shown at right.

function as that of Chang Heng: it indicated the direction of the horizontal component of seismic tremors during the period between two observations.



Figure 8a

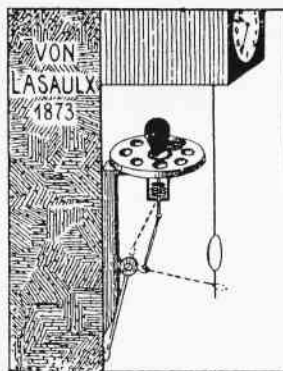


Figure 8b

Seismoscopes of de Hautefeuille and von Lasaulx, from Sieberg

The European instrument was essentially a gravity pendulum. The shape of the bowl determines the radius of the arc described by the center of gravity of the mass of mercury rocking back and forth. The flatter the bowl, the longer the period of vibration. If the mercury is replaced by water, as in a device set up by Chandler in 1742 in Lisbon, the frequency is not affected, but evaporation of the water may pose a practical problem.

Improved versions of de Hautefeuille's seismoscope were made by Cavalli in 1837, by Cacciatore in 1848, and finally by Lepsius in 1884. Before the turn of the century the character of instruments used to observe earthquakes had irrevocably changed. The new seismometers or seismographs not only determined the direction of the epicenter, but provided quantitative data on the period and amplitude of each component of the seismic tremors.

Their arrival caused the seismoscope to sink into oblivion. As it was sinking several new types were invented. One of these is interesting in the present connection, namely the instrument invented by von Lasaulx in 1873 (Figure 8b). The sensitive element was an egg-shaped mass of metal that could topple into one of the eight indentations that surround its support. Its toppling stopped a clock, thus providing data on time as well as direction of a major seism.

Unlike modern seismometers that pick up any seism occurring on our planet, the range of interest of these devices did not exceed two thousand kilometers. Within that range, the waves of largest amplitude are usually the surface waves, with a typical period of ca. 5 to 10 seconds. Since they are longitudinal, they cause displacements in a direction along the great circle through the epicenter. This accounts for the interpretation always given to the results of European seismoscopes: the direction of the vibration was supposed to indicate the direction of the epicenter. In the liquid pendulum seismoscopes the direction of vibration was given by the pair of opposite beakers containing most of the mercu-

ry spilled over after a seism, and in the "toppling egg" seismoscope by the direction in which the egg had toppled.

In addition, it was assumed that the epicenter was closest to the direction toward which the egg had toppled, or in the direction of the beaker containing most mercury. This erroneous notion sometimes led to theoretical misinterpretations. It was reported in 1884, for instance, that Mt. Etna, a Sicilian volcano active at the time, not only generated seismic waves radiating from it, but also waves converging toward it (e.g., Winkler Prins 1884: I, 27). This misconception was set to rest only when modern seismometers registered seismic P-waves that had travelled several circuits of the earth. Chang Heng's assumption, then, was widely shared in the Occident until the twentieth century.

Modern seismographs are provided with very large suspended masses, so that the characteristic frequency is much larger than the frequency of the seismic waves. The latter thus can be reliably registered. The mechanical energy stored in the vibrating mass is, of course, proportional to this mass, and has to be dissipated by suitable damping.



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