Acoustics of Ancient Chinese Bells

Bronze bell chimes were important orchestral instruments until they vanished from history 2,000 years ago. A chime recovered by archaeologists has revealed their sophisticated acoustical design

by Sinyan Shen

In 1978 a set of Chinese bronze chime bells large enough to occupy the entire stage of a modern recital hall was unearthed in Hubei Province in southern China. The chime, which dates from the fifth century B.C., consists of 65 bells encompassing five octaves, a range greater than that of most contemporary instruments. A filigree of gold-inlaid inscriptions on the bells and their frame documents the existence of an elaborate theory of music that specified the design, scales and instrumentation of ancient orchestras. This record and recent investigations of the chime itself have prompted a complete rewriting of the history of acoustics.

The ancient inscriptions confirmed what modern scholars were only beginning to suspect: that the bells were constructed in such a way that each could produce two separate pitches. This property sets the Chinese chime bells apart from Western church bells, which are known for their single, lingering tones; unlike church bells, the chime bells could perform complex, rapidly metered music. For reasons that are not clear, the principles and practices surrounding the unique bell design were never passed down. Consequently the way to play chime bells remained a mystery for more than 2,000 years.

The bells incorporate many unusual features whose sophistication and precision can be appreciated only in the light of the dual-pitch design. Since the chime was discovered, studies of vibrational properties and tuning methods have revealed the depth of understanding possessed by Chinese metallurgists and musicians. The design of the bells requires a theoretical grasp of physics and engineering formerly thought to have evolved only in the late 18th century. Indeed, the acoustical principles exploited in the Chinese bronze bells have astonished even 20th-century acousticians.

The study of acoustics in the Western world is relatively young. In 1787 a German physicist named Ernst F. Chladni sprinkled sand on vibrating plates to show that some regions of the plates remained stationary during vibration. These motionless regions were termed nodal lines; their distribution describes the modes a vibrating body assumes. Each so-called normal mode is associated with a characteristic frequency of vibration, and the frequency of vibration determines the perceived pitch.

Vibrating bodies move in many different modes simultaneously and generate many different frequency components called partials. The partial with the lowest frequency is called the fundamental; there are many higher frequencies called overtones. When a bell is struck or a string is plucked, all these frequencies come into play, but some are stronger (louder) than others. The relative strength of partials in a musical sound constitutes its tonal quality, just as a combination of wavelengths determines the color of light.

In 1890 Lord Rayleigh studied the bells in the tower of his church in Terling, England, and performed experiments on several bells in his laboratory. He identified six partials in the bells. Rayleigh, who laid the foundation for subsequent work on bell acoustics, thought that a bell could produce just one fundamental pitch. Since his experience was confined to Western bells, he could not have foreseen the lesson that Chinese bells thousands of years old would teach.

About 80 years ago single chime bells began to appear among other archaeological finds in China. Later sets and entire ensembles of the bells turned up; today thousands of bells and more than 50 chimes have been recovered. Although the bells were thoroughly scrutinized, investigators did not recognize the dual-pitch potential until 1977. Some doubts persisted until the 1978 discovery of the chime in Hubei Province.

There were earlier clues that had escaped notice. While studying the Jing-li bell chime, which had been un-

BELL CHIME of Zenghou Yi, ruler of a fifth-century B.C. Chinese principality, is

earthed in Henan Province in 1957, investigators at the National Music Research Institute played "The East Is Red" using pitches obtained by striking the bells at their center. An $^{\#}E_5$ was missing. Anxious to complete the piece, the team found the note by striking a $^{\#}C_5$ bell on its side. Their success was regarded as accidental.

In 1977 Huang Xiang-peng, Lu Ji, Wang Xiang, Gu Bo-bao and their colleagues at the institute examined a bell chime discovered in Shanxi Province and found that every bell, when struck on a side, produced a pitch higher than the one sounded from the center. The interval between the pitches was always a minor or major third, a difference in frequency equivalent to that between four or five consecutive keys on a piano. The team's observation sparked animated discussions about whether the phenomenon was accidental or deliberate, and whether the second pitch was a fundamental or an overtone.

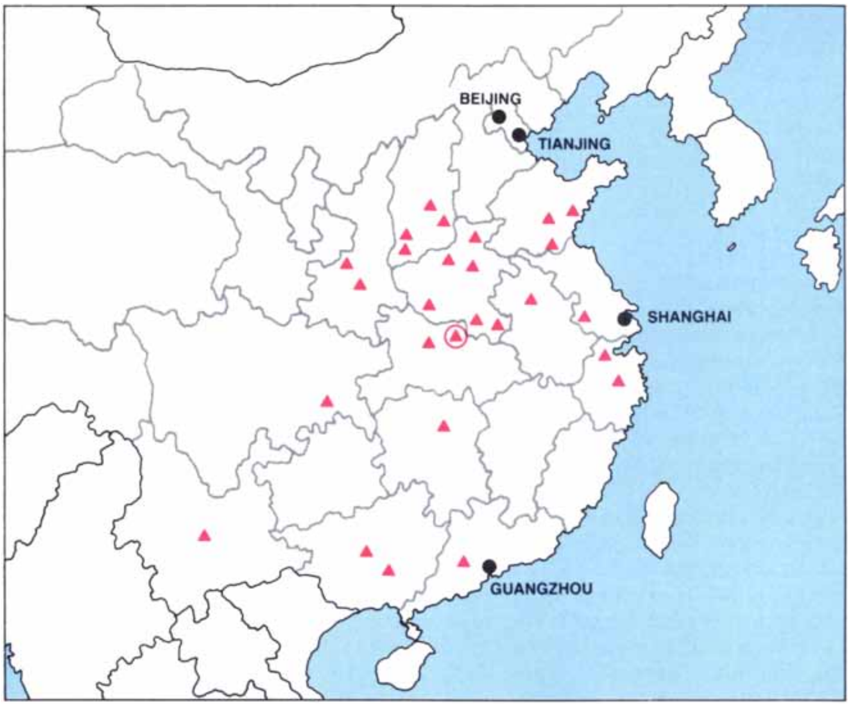
The investigators then studied more than 200 bells from the Shang (16th to 11th centuries B.C.) and Zhou (11th century to 221 B.C.) periods, spanning the historical lifetime of the chimes. They concluded that the bells were deliberately constructed to produce two pitches. In one chime the side striking positions were decorated with glyphs of the phoenix, a practice presumably linked to ancient legends in which the singing of the phoenix connotes music.

When, a year later, the magnificent 65-bell chime was found in Hubei Province, the researchers' conclusion was borne out. The chime had been interred in the tomb of Zenghou Yi, marquis of an ancient principality known as Zeng. It was part of two large orchestras also preserved in the marquis's tomb. The bronze *zhong* bells, which combined make up a type of chime called *bian-zhong,* were intact and almost perfectly tuned. The musical treasures of Marquis Yi confirmed the dual-pitch design of chime bells through detailed records inscribed on the bells themselves.

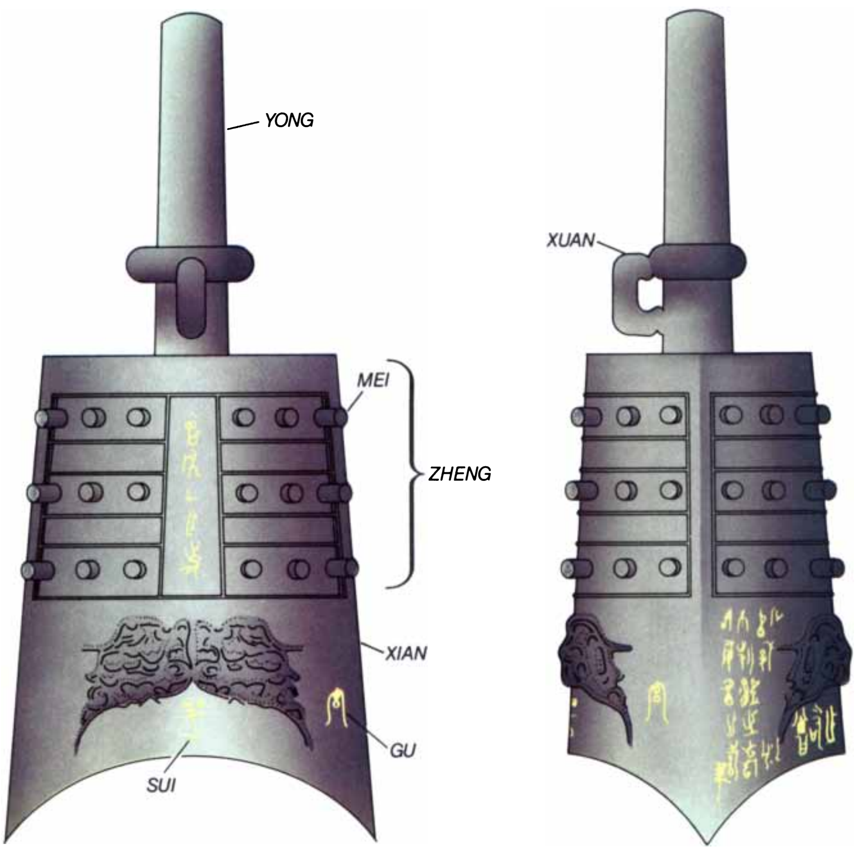
Because chime bells are intended to perform music in the company of orchestras, their desirable qualities are somewhat different from those of a ceremonial bell or a church bell. Each member of the chime should have a broad dynamic range and, to allow the performance of complex melodies, its tones must please the ear and attenuate quickly, without a prolonged echo.

The geometric configuration of the chime bells is crucial to their achieving these acoustical properties. The *zhong* bell has an asymmetrical construction. Unlike the church bell, which is circular in cross section, a *zhong* bell is oblate: its horizontal cross section is a flattened oval. The lip of the bell does not lie on a plane but arches upward in the front and back, then downward into hornlike feet on the left and right sides. The front and back faces meet at a ridge called the *xian*. Covering four

the most impressive set of *zhong* bells found to date. The chime consists of three tiers of bells mounted on an L-shaped frame. Exhaustive acoustical studies have shown how unique structural features enable each bell to sound two pristine fundamental pitches.



MAP OF BELL-CHIME DISCOVERY in China includes only the eastern and southwestern provinces because all the chimes were found there. More than 50 sets of bells have been unearthed since 1900. A circle marks the origin of Zenghou Yi's collection.



ZHONG BELL FEATURES are intimately related to the tonal quality and performance of the bell, shown here in front (*left*) and side views. The bell can produce two pitches because its cross section is asymmetrical; the tones are refined by bronze *mei* nipples. Some bells also carry inscriptions that indicate exact striking positions for each pitch.

regions of the upper bell body are 36 bronze nipples known as *mei.*

In a *bian-zhong* chime each *zhong* bell is suspended by a collar called the *xuan* from a hook mounted on the beam of the chime frame. The clapperless bells are arranged in tiers and played with different kinds of strikers. Usually bells of the high and middle registers are hung at or above eye level; the performers use hammerlike mallets. Bells of the low register are hung in the bottom row and are played using rods wielded in a near-horizontal trajectory.

A bell chime consisting of several dozen bells requires from five to seven performers. Performers of different registers stand on opposite sides of the chime. The bell mouth hangs downward at an angle of about 30 degrees from the vertical, balanced by a long, heavy nose called a *yong* that tilts toward the back so that the side to be played faces the performer. Depending on their pitch, the *zhong* bells range from a few inches to several feet in height: these last are relatively large instruments by modern standards.

The two fundamental pitches that give the bells their notoriety arise from two distinct regions on the bell face. One pitch comes from the lower center of the bell, a position called *sui,* and the other from the areas to the left and right of the *sui,* called the *gu* positions. The term *sui* is said to mean "mirror" and probably refers to the similarity between the curve of the bell lip and the concave burning mirror used at the time to start fires. *Gu* means "drum" or "music-producing." Because of a strong cultural emphasis on right-handedness, the right *gu* was played much more often than the left.

When played in a set, dual-pitch bells allow efficient performance and reduce the overall size of the bell chime. The design of Western bells is not nearly as practical. The "strike" tone of a Western round bell (the pitch heard by a listener) is not the "hum," or fundamental tone, but the note an octave above the hum tone. For instance, a modern American bell with a fundamental pitch of middle C (C_4 at 256 cycles per second) has a perceived pitch of C_5 (512 cycles per second). It weighs 800 pounds. According to the approximate rule that the pitch of a round bell is inversely proportional to the cubic root of its mass, a decrease in frequency by a factor of two would require eight times the original mass. An American bell with a middle-C strike tone would therefore weigh more than three tons—nearly 1,000 pounds more than all the bells and racks in the Zenghou Yi chime combined.

ACOUSTICAL ANALYSIS revealed the precision of the *zhong* design. Zhou engineers learned to manipulate the overtones in the bell's "voice" as well as the two fundamentals. Wang Xiang (*seated*) and Huang Xiang-peng of China's National Music Research Institute are shown here determining the pitches of Zenghou Yi's chime. In spite of their age, the bells were almost perfectly tuned.

The inability to produce a bell that can sound its acoustical fundamental, then, has had serious implications for the material requirements and casting constraints of bell manufacture. Yet the church-bell design is the result of centuries of careful experimentation. The Chinese design, the result of thousands of years of labor, was lost after the Han period (206 B.C. to A.D. 220). What acoustical secrets does it embody that eluded Western designers?

A bell is a very complex acoustical body. Its partials cannot be expressed as simple arithmetic ratios, in contrast to the completely elastic string or a vibrating air column whose frequencies correspond to the ratio 1 : 2 : 3 : 4 : 5 : 6 and so on. Both the oblate *zhong* bell and the round church bell are special adaptations of the acoustical system known as vibrating plates. For plates and bells alike, increasing the thickness and elasticity of the vibrating material increases vibration frequency, whereas increasing diameter and density decreases the vibration frequency.

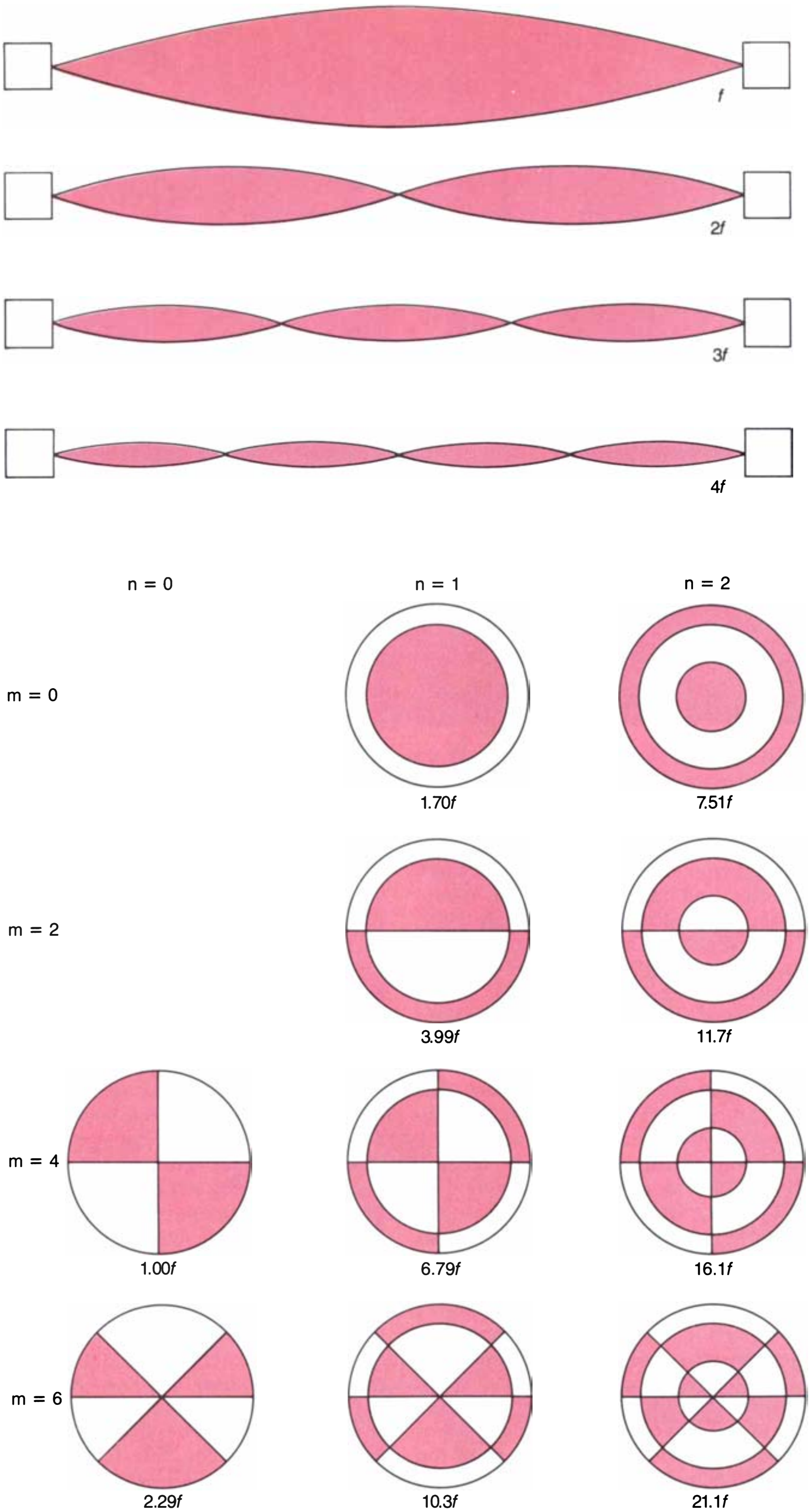
Mary D. Waller of the London School of Medicine for Women studied the normal modes of vibrating circular plates and published her results in 1937. Her nodal figures consist basically of radii (designated m) distributed symmetrically around the plate's center, and circles (designated n) concentric with the perimeter of the plate. The simplest mode, the one corresponding to the fundamental tone, exhibits four nodal lines that divide the plate into four vibrating sections shaped like pieces of pie. Adjacent segments are always moving in opposite directions at any given instant. The next mode, which generates a frequency 1.7 times that of the fundamental, has only one nodal circle, which delineates an inner circular segment and an outer ring. Other modes arise from additional combinations of radii and circles, creating a rich interplay of partial frequencies.

Acoustically, a round bell behaves like a plate stretched into a flared bell shape and suspended at the center. The normal modes of a round bell, viewed from above, are quite similar to the patterns seen on circular plates. Vibrational motion is most intense at the rim. When the bell is given a blow, the struck side is forced inward and adjacent regions are pushed outward. The rim then passes through its initial circular shape to form another elongated circle at a right angle to the first.

In the course of these vibrations certain parts of the bell remain relatively still compared with others, namely the points at which the different circular distortions intersect. These points represent the nodal lines of the bell, called nodal meridians. They are not nodes in the strict sense, however, because the intersections are not exact, and so some motion continues to occur in the plane of the surface. This motion is what makes a glass goblet ring when one rubs a wet finger around the rim.

Nodal meridians on a round bell are spaced evenly, as are the nodal radii of a plate. Because of this symmetry, a clapper can be used with a round bell, since striking any point on the rim produces the same vibrational effects. The meridians of the asymmetrical *zhong* bell, on the other hand, are not evenly distributed. The consequence of this asymmetry is that, for any given number of nodal lines, more than one spatial arrangement is possible.

Indeed, the *zhong* bell has two well-defined sets of modes that can be selectively activated by striking different positions on the bell: the *sui* and *gu* positions. Although at the two fundamental pitches the modes have the same number of nodal lines ($m = 4$ and $n = 0$), the placement of the lines is indeed different, so that the frequencies generated are different. This "degeneracy" of vibrational modes accounts for the chime bells' extraordinary acoustical properties. In general the *gu* mode produces higher frequen-



PARTIAL FREQUENCIES, which make up the tonal quality of a sound, result from the different modes of a vibrating body. The lowest frequency is called the fundamental; other frequencies are overtones. When a taut string is plucked (*top*), it produces partials that are whole-number multiples of the fundamental frequency *f*. A vibrating plate (*bottom*), however, gives rise to partials that cannot be related by simple arithmetic ratios. Instead frequencies depend on the combination of nodal radii (*m*) and nodal circles (*n*): regions of the plate that remain still during vibration. Red and white represent movement in opposite directions. A bell, whether it is round or oblate, is a special kind of vibrating plate.

cies than the *sui* mode, but the two are not mutually exclusive: they share certain high-frequency partials that issue from the more complex modes.

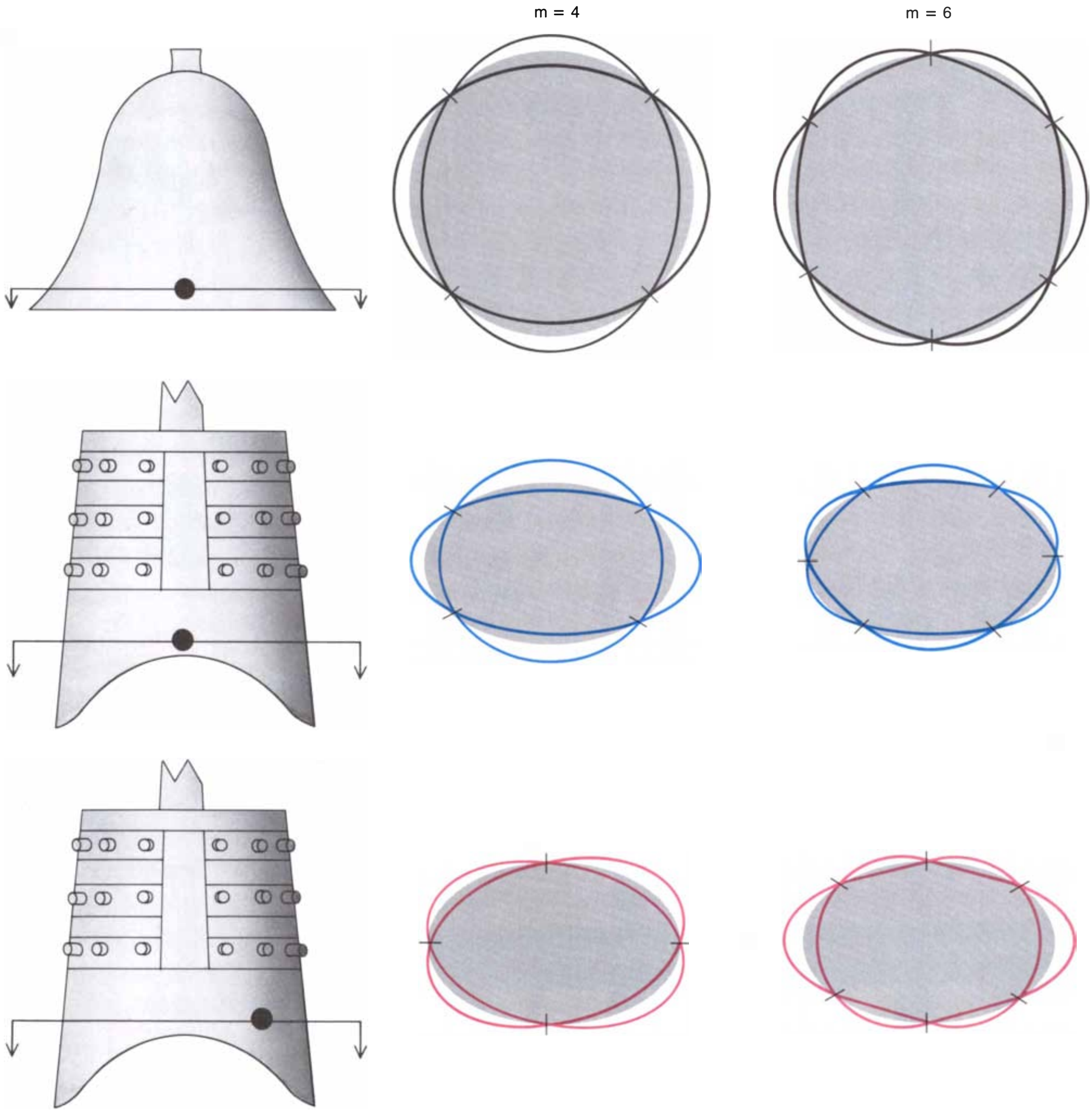
The ancient Chinese refined their dual-pitch design to make the two sets of modes distinct in acoustical character yet comparable in musical function. They worked to separate the two pitches of each bell by excluding common qualities. For instance, when the *sui* position is struck, the faces and sides of the bell experience the greatest movement and the *gu* areas in between represent the silent, motionless nodes. The *sui* areas become nodes when the bell receives a blow at the *gu* position. Hence each striking position falls at the point that is least disturbed when the other position is struck, which is also the area least involved in producing the alternate tone.

In order to locate so precisely the nodal meridians of the two fundamental modes, the ancient Chinese must have possessed a theoretical grasp of the physics of music far beyond historians' initial estimates. Given such an understanding, it would be fairly straightforward, although not easy, to find the strike positions that isolate the fundamentals. To achieve the best resolution between pitches, however, overtones as well as fundamentals should be separated. Nodal meridians for the important *gu* overtone modes converge naturally at the *sui* strike position; therefore they do not contribute to the *sui* tone. The meridians of *sui* overtone modes, however, do not congregate at the *gu* position, so that traces of *sui* partials could interfere when the *gu* tone is struck. Herein lies the rationale for the arched lip of the *zhong* bell.

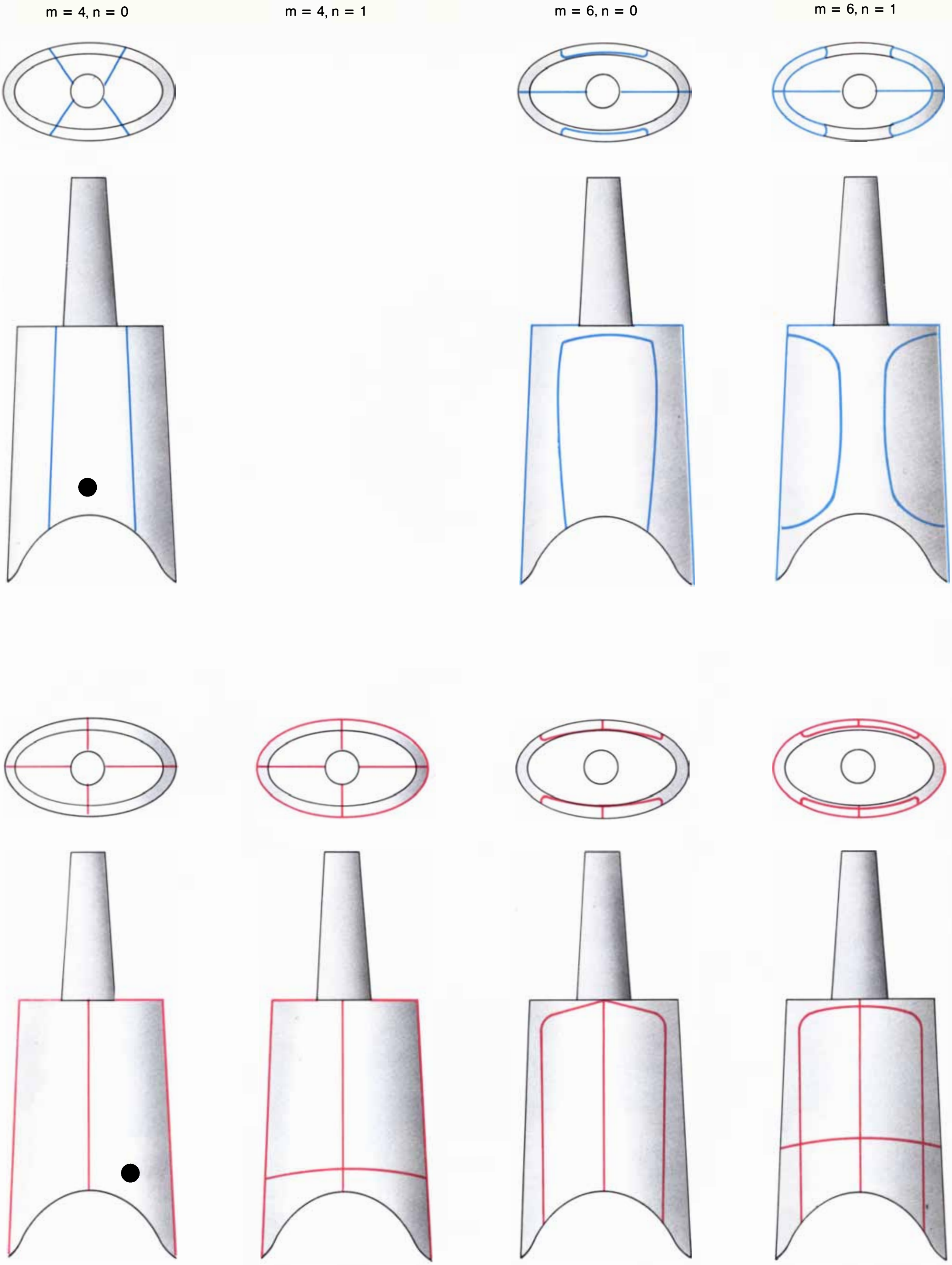
When we examined the two sets of normal modes, we found that the arch in the bell lip, by changing the shape of the vibrating "plate," also alters the nodal patterns of the most important *sui* overtones. Because of the arched lip, the *sui* overtone meridians converge at the point designated, not coincidentally, as the *gu* strike position. It is typically three-fifths of the way from the *sui* position to the *xian* ridge. The striking position is so critical to obtaining the proper pitch and tone quality that the ancients made inscriptions on the bells to indicate *sui* and *gu* placement unequivocally. Neither the concave rim design nor the precision in identifying the convergence of nodal lines could have been accidental.

The *mei* nipples clustered at the top of all but the highest-register bells are also more than ornamental. They help to balance the strength of the two fundamentals so that their volumes are comparable. More important, the *mei* act as another device to separate the two bell tones. Recent laboratory studies have found that the nipples change the complete overtone structures, or frequency spectra, of *sui* and *gu* tones. The *mei* provide extra weight around the bell shoulders, altering nodal patterns in the upper part of the bell. Accordingly they are most pronounced on large bells. Without the *mei,* the *sui* and *gu* fundamentals are easily distinguished, but they have certain high-frequency overtones in common. With the nipples, overtone frequencies shift so that little overlap between the two sets of partials occurs.

The interval between the two pitches on a *zhong* bell is selected by casting and tuning. The choice of the interval is arbitrary, but it should suit the melodic progression of the compositions it will perform. In addition the interval should not be a discord since, in spite of the efforts of the designers, traces of the secondary tone may persist after the primary tone has died down. Zhou engineers tuned their bells so that the intervals of the overtones, as well as those of the fundamentals, were harmonic. The second partial of the *gu* tone, for example, is always an



MOTION AT THE RIM when a bell has been struck illustrates the distribution of nodal lines for a round bell (*top*) and for the two pitches of a Chinese *zhong* bell, called *sui* (*middle*) and *gu* (*bottom*). Gray indicates resting positions; lines show changes in the bell's shape after it has been struck. Modes in which *m* is equal to 4 and 6 are represented. At these modes the nodal radii of a round bell are evenly spaced; hence only one pattern of distribution is possible. Because a chime bell is oblate, however, a given number of nodal lines can be arranged many different ways, and different nodal patterns give rise to different pitches. As is shown here, the pattern of nodal radii is determined by the point at which the bell is struck. Chinese designers managed to maximize the separation between the two *zhong* pitches by having the nodal lines of one pitch serve as the striking position for the other.



NODAL PATTERNS for the *sui* (*top*) and *gu* (*bottom*) pitches describe the modes of the fundamentals and the most conspicuous overtones. Top-view renderings above each bell recall the vibrating-plate system for enumerating radii and circles. Horizontal lines count as circles even when they do not encircle the bell, but near the bell shoulders they do not contribute to the bell's sound and so are not counted. As the top illustration on page 110 shows, the *sui* tone has two dominant overtones and the *gu* tone three.

octave plus a major or minor third above the *sui* tone; the partials of a *zhong* bell with a minor third separating its two pitches are in the ratio 1 : 1.2 : 2.4 : 2.81 : 3 and those of a bell with an interval of a major third are 1 : 1.25 : 2.5 : 2.81 : 3.

When bell-chime intervals from several periods are compared, a historical trend toward the major- and minor-third intervals represented in Marquis Yi's bell collection becomes apparent. Lacking examples of ancient music, one can only assume that this preference matches a taste for major and minor thirds in the musical composition of the time. In Europe these intervals were not recognized as harmonic until the 12th century.

When Marquis Yi's *bian-zhong* was found, its bells were almost perfectly tuned in spite of their prolonged burial. A second set of 36 bells discovered in the same principality of Zeng in 1981 were even better tuned. Ordinarily a vibrating plate is tuned by the addition or removal of material, but with this method it would seem impossible to tune one bell pitch without altering the other, since both are contained on one continuous body. How did the Chinese tune two pitches on a single *zhong* bell?

Again the ancients made use of their remarkable expertise in pinpointing nodal lines. They could tune just one pitch by paring bronze off a bell's inner surface if, in paring, they carefully followed the nodal lines of the other. Hence tuning the *sui* pitch entailed removing metal from the *gu* nodal lines, and vice versa. At the same time, many bells were cast so accurately that they required no modification.

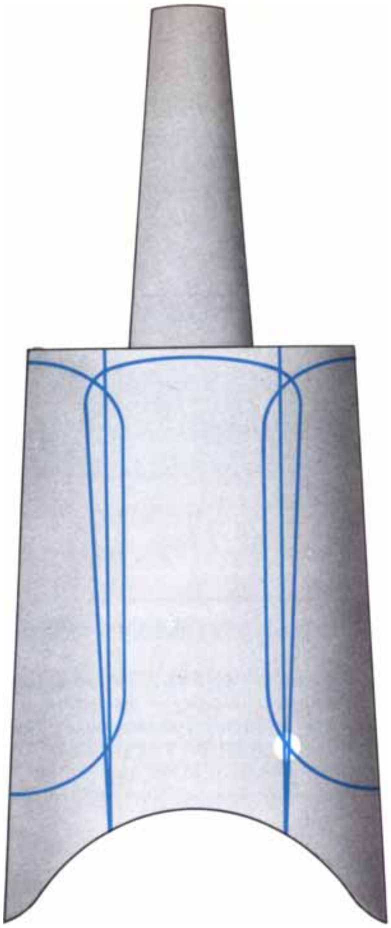
The methodology of bronze casting with pottery sectional molds was fully developed in ancient China. Even so, manufacturing a low-register *zhong* bell presented quite a formidable task. Large, complicated objects were often made by casting separate parts, then uniting the components in a final mold. But the bronze chime bell, no matter how large, was always cast as a single piece.

In the modern world the closest approximation of a Chinese bell chime is the carillon. A carillon consists of a group of bells carefully selected to yield equal-tempered chromatic intervals. The bells are played from a keyboard. Because some of the partials are in discord, only a limited number of chords are within the carillon's scope, and ordinarily only a single melody is played. Considerable knowledge and skill are needed to render satisfactory effects; even expensive installations can give disappointing performances. If the carillon is the best that modernity has to offer, one might wonder how the Chinese arrived at the *bian-zhong* design so long ago.

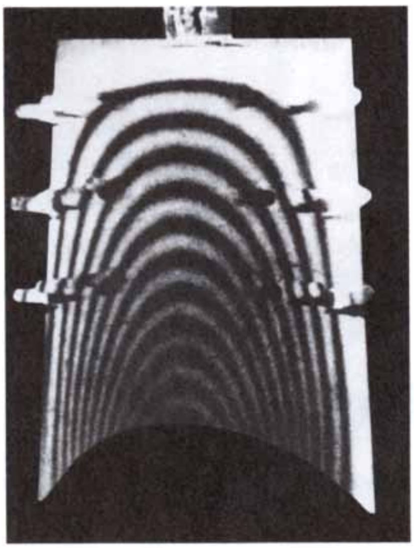
Since ancient times Chinese musicians have been sensitive to subtle differences in tonal quality. This sensitivity is manifested in many of their instruments. For example, I once asked a Chinese wind player about the design rationale of the *shuang-guan,* an oboe consisting of two apparently identical cylindrical oboes. He replied, "No two reeded tubes have the same tonal spectrum. With two tubes on the *shuang-guan,* the player has control over a broader range of tonality and can be more selective of the timbre."

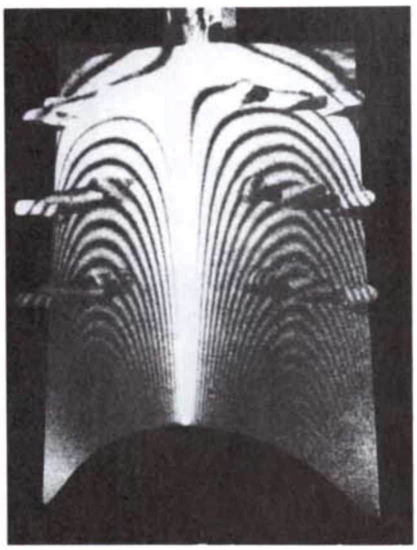
Perhaps this heightened sensivity to tonal structure led the ancient Chinese to experiment with a slightly elliptical bell design, which gives rise to a fuller set of vibrational modes and a broader range of overtone possibilities. *Ling* bells, relics of the early Shang period, were oblate but still had clappers and produced only one tone; their musical character can be inferred from the fact that they were used as bells for dogs and cows.

In subsequent efforts the Chinese may have struggled with oblate bells that sounded two distinctly different pitches but produced only awkward or muddy tones. The large, oblate *zheng* handbell, which predates the chime bell by hundreds of years, exemplifies this stage of development. Indeed,

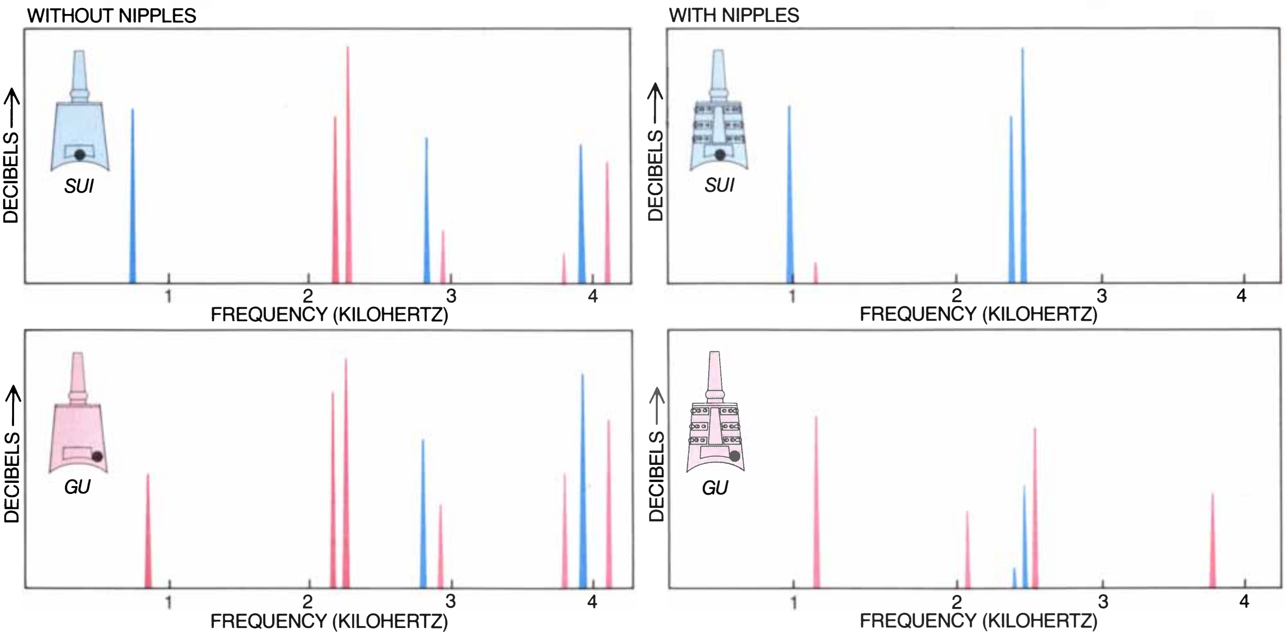


NODAL-LINE CONVERGENCE for the three dominant partials of the *sui* tone is an important consequence of the chime-bell design. If the perimeter of the bell were flat, *sui* nodes would never intersect; hence a blow to any part of the bell would excite at least one *sui* tone. The arched lip of the *zhong* bell, however, rearranges nodal lines so that they congregate at the *gu* position (*circle*). This convergence helps to clear the *gu* tone of "muddy" *sui* echoes.





LASER HOLOGRAMS capture the fundamental modes of vibration for the *sui* (*left*) and *gu* (*right*) pitches. Wide white areas represent nodes; the dark lines are areas of intense movement. The complementary convergence of nodal lines is apparent. These images result from the differential reflection of light by moving and stationary surfaces of the bell.

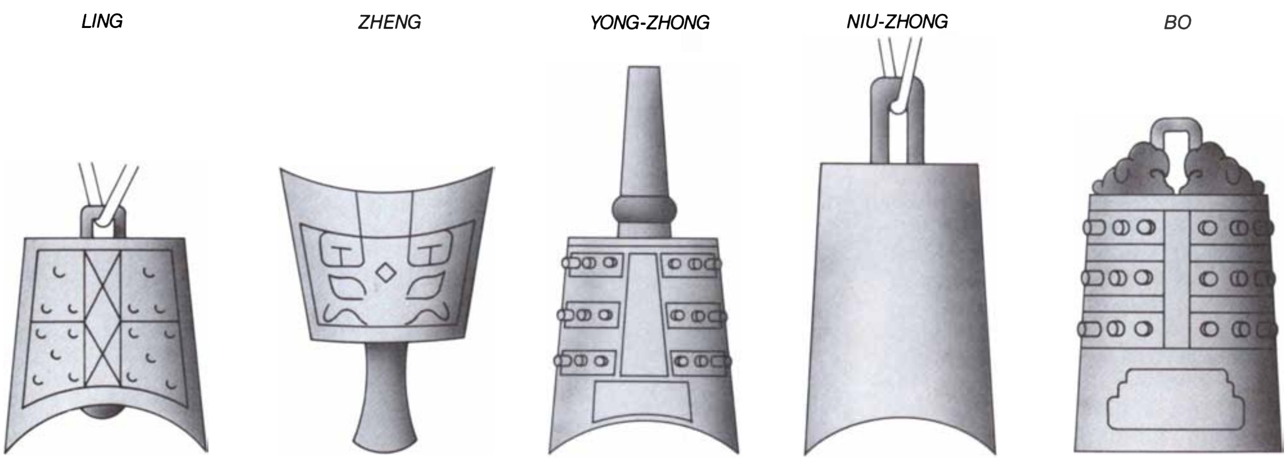


GRAPHS OF PARTIAL FREQUENCIES emphasize the importance of the *mei* nipples in separating the *sui* (*blue*) and *gu* (*red*) tones. The frequencies generated by bells without *mei* (*left*) are almost identical for the two positions. Only the fundamentals are noticeably different. When nipples are added (*right*), nodal patterns in the upper part of the bell are rearranged, changing some frequencies and eliminating others. Almost all traces of *gu* tones disappear from the *sui* profile, and only hints of *sui* partials remain in the *gu* tone. *Mei* nipples also serve to increase the volume of the *gu* fundamental so that it matches the volume of the *sui*.

zheng bells lend their name to the upper half of the *zhong* bell, and the *yong* nose that holds the *zhong* at a 30-degree tilt is derived from the *zheng* handle. The clapperless *zheng* bell, however, has a muddy *gu* tone because its flattened mouth does not force the convergence of *sui* nodal lines.

With modification of the bell's surface, cross section and thickness, the two pitches were brought into a well-defined harmonic relation and their individual tones were sharpened; eventually the sophisticated *zhong* design emerged. Contemporaries of the *zhong* bells include the *niu-zhong,* which is also dual-pitch, and the ceremonial *bo,* which lacks the musical agility of the *zhong.* Both these bells are played in the vertical position.

The art of music has a long and distinguished history that parallels the rise of human civilization. The principles embodied in the Zenghou Yi bell chime suggest that the science of music may have a history almost as long, and just as distinguished. China in the Shang and Zhou periods possessed a level of acoustical science that was essential in supporting the elaborate musical art of those periods. Physics and engineering worked hand in hand to perfect wind, string and percussion instruments and to arrive at orchestration. These are accomplishments that have modern counterparts. In contrast, the overall design of a large set of dual-pitch bells for the performance of music is an achievement that has no equal in the modern physics of music.



BELL ANCESTRY suggests the route the ancient Chinese followed to arrive at the *zhong* design. The *ling,* oldest of the five bells drawn here, goes back more than 3,600 years. It had a clapper and produced just one unremarkable note. The *zheng* handbell is an early example of the dual-pitch design; it was used by Chinese soldiers, who carried it mouth up. The *niu-zhong* also produces two pitches, but it lacks the clarity of the popular *yong-zhong* at low registers. *Niu-zhong* are visible in the top tier of the chime on page 105. Another *zhong* contemporary, the *bo,* served as a monotone ceremonial bell. The bells are not drawn to scale.