The Physics of the Piano

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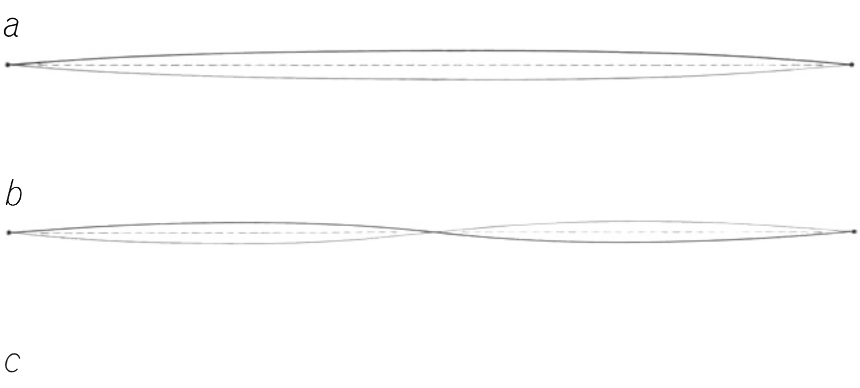
The Physics of the Piano

Most musical instruments produce tones whose partial tones, or overtones, are harmonic: their frequencies are whole-number multiples of a fundamental frequency. The piano is an exception

by E. Donnell Blackham

Almost every musical tone, whether it is produced by a vibrating string, a vibrating column of air or any other vibrating system, consists of a fundamental tone and a number of the higher-pitched but generally fainter tones known as partial tones or overtones. The complex sound produced by this combination of separate tones has a timbre, or characteristic quality, that is determined largely by the number of partial tones and their relative loudness. It is timbre that enables one to distinguish between two musical tones that have the same pitch and the same loudness but are produced by two different musical instruments. A pure tone—one that consists solely of the fundamental tone—is rarely heard in music.

It is widely believed that the partial tones produced by all musical instruments are harmonic—that their frequencies are exact whole-number multiples of the frequency of a fundamental tone. This certainly holds true for all the woodwinds and under certain conditions for many of the stringed instruments, including the violin. It is only approximately true, however, in the most familiar stringed instrument: the piano. The higher the frequency of the partial tones of any note on the piano, the more they depart from a simple harmonic series. In our laboratory at Brigham Young University my colleagues and I, under the direction of Harvey Fletcher, have succeeded in measuring with considerable precision the degree to which the modern piano is inharmonic and have demonstrated the importance of this factor in determining the distinctive quality of the piano's tone.



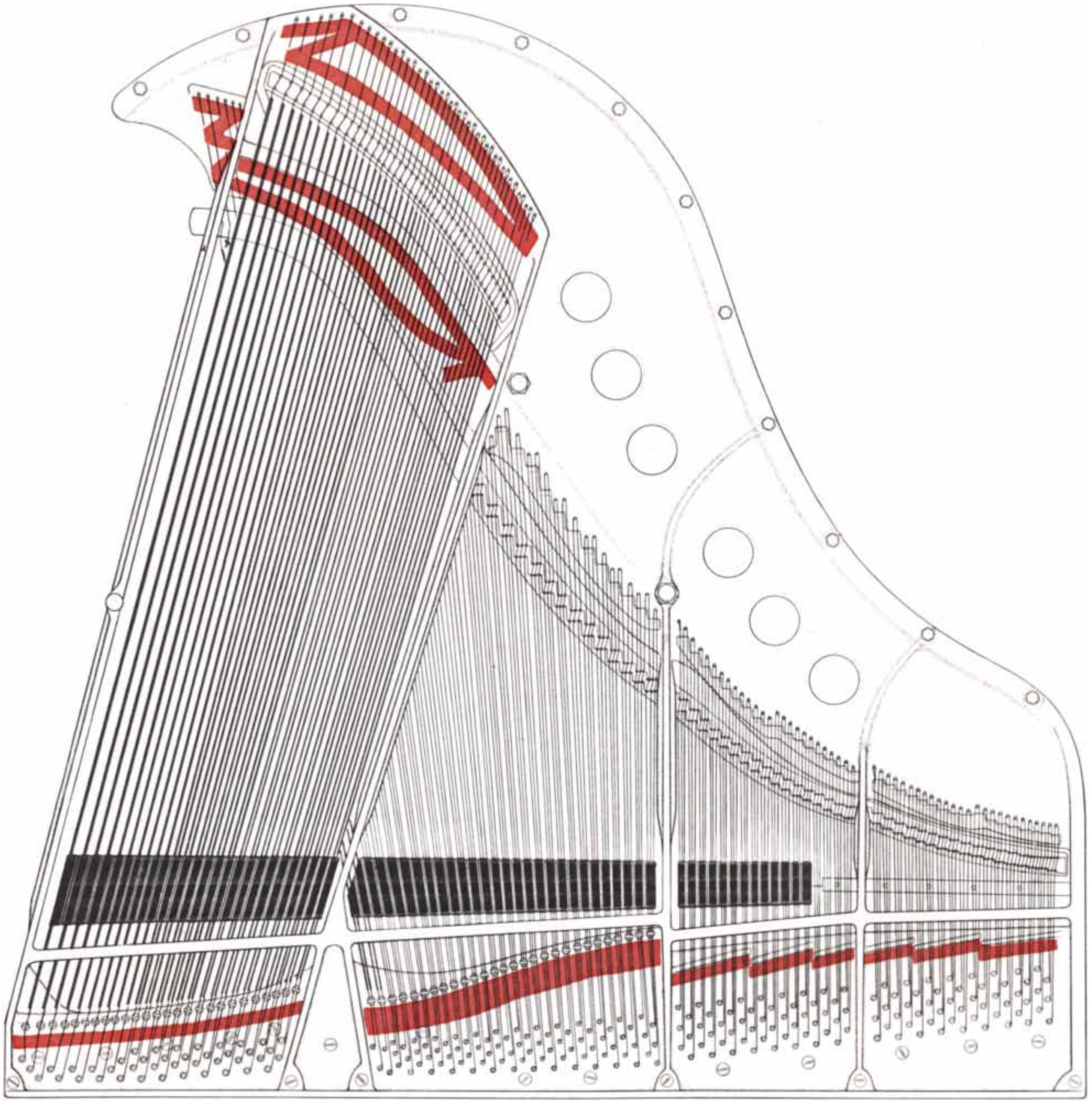
IDEAL STRING, that is, one without any stiffness, can be made to vibrate at many different frequencies: the fundamental frequency (*a*) produces a pure tone, rarely heard in music, whereas higher-pitched partial tones, or overtones, are produced by harmonic vibrations (*"b" and "c"*), whose frequencies are whole-number multiples of the fundamental frequency.

SIMULTANEOUS VIBRATION of a string at two or more different frequencies is normal for stringed instruments. Here the string vibrates at the fundamental frequency and the second partial frequency (*"a" and "c" in upper illustration*). In the piano the stiffness of the strings causes higher partials of a complex tone to depart from the simple harmonic series.

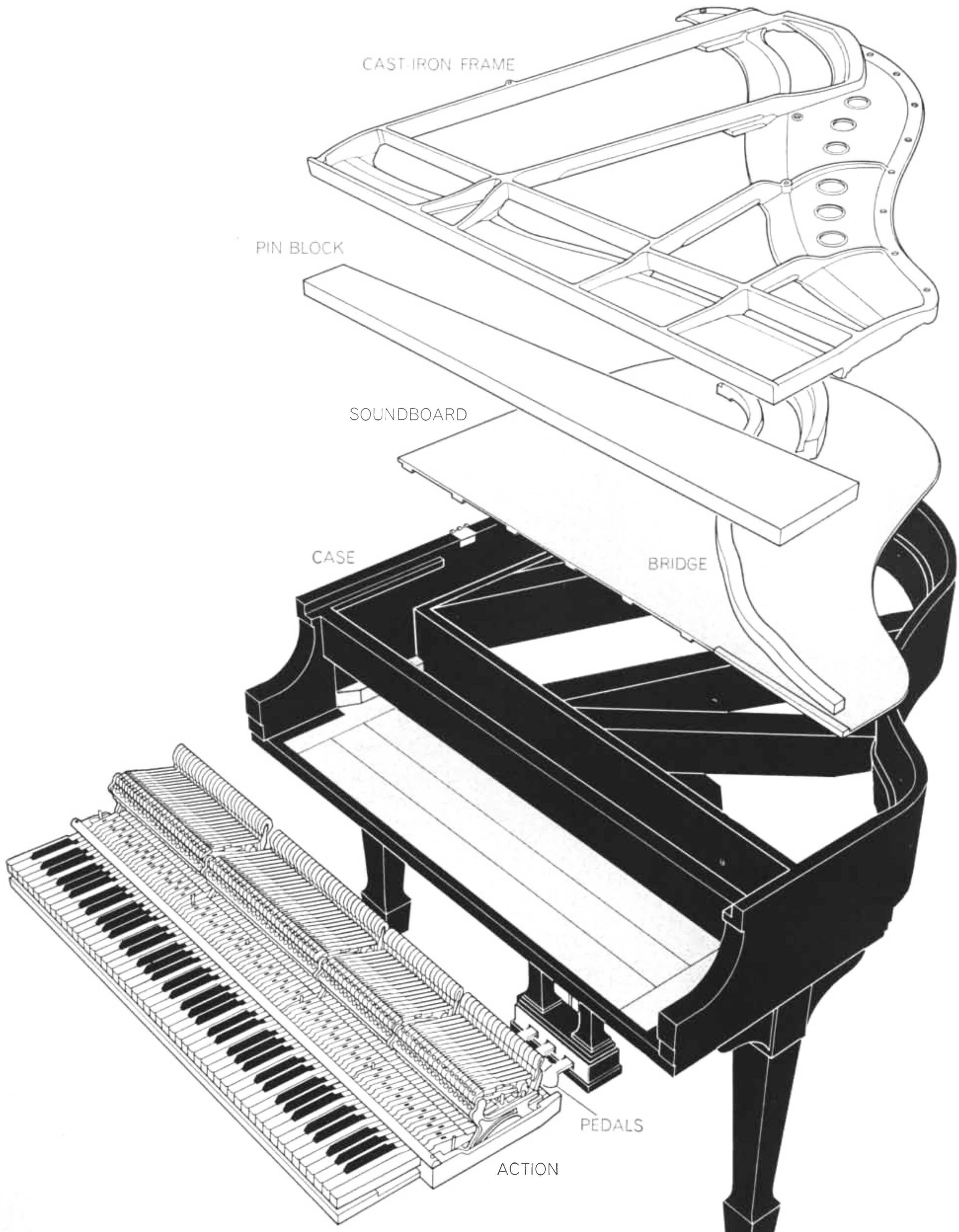
The physics of the piano can best be understood by first reviewing the evolution of the modern piano and its principal components. Archaeological evidence shows that primitive stringed instruments existed before the beginning of recorded history. The Bible refers several times to an instrument called the psaltery that was played by plucking strings stretched across a box or gourd, which served as a resonator. A similar instrument existed in China some thousands of years before the Christian era. In the sixth century B.C. Pythagoras used a simple stringed instrument called the monochord in his investigation of the mathematical relations of musical tones. His monochord consisted of a single string stretched tightly across a wooden box. It was fitted with a movable bridge that could divide the string into various lengths, each of which could vibrate freely at a different fundamental frequency.

Another important component of the modern piano—the keyboard—did not arise in conjunction with a stringed instrument but with the pipe organ. The organ of Ctesibus, perfected at Alexandria in the second century B.C., undoubtedly had some kind of keyboard. The Roman architect Vitruvius, writing during the reign of Augustus Caesar, describes pivoted keys used in the organs of his day. In the second century A.D. Hero of Alexandria built an organ in which the valves admitting air to the pipes were controlled by pivoted keys that were returned to their original position by springs.

We do not know who first conceived the idea of adding keys to a stringed instrument. From this obscure beginning there eventually evolved in the 15th century the clavichord. In the early clavichords a piece of metal mounted vertically at the end of the key acted both as a bridge for determining the pitch of the string and as a percussive device for producing the tone [*see upper illustration on page 92*]. Since one string could be used to produce more than one tone, there were usually more keys than strings. A strip of cloth was interlaced among the strings at one end in order to damp the unwanted tone from the shorter part of the string.



TOP VIEW of the interior of a modern "baby grand" piano shows the powerful construction of the full cast-iron frame, which sustains the tremendous tension exerted by the strings. In this particular piano the frame, which is cast in one piece, weighs about 250 pounds and sustains an average tension of some 50,000 pounds; in a larger concert-grand piano the frame weighs as much as 400 pounds and sustains an average tension of 60,000 pounds. The strings are made of steel wire with an ultimate tensile strength of from 300,000 to 400,000 pounds per square inch. In order to make the bass strings (*left*) vibrate slower and thus produce a lower pitch, they are wrapped in copper or iron wire; two such wrappings are often used in the extreme bass. In all modern pianos the bass strings are "overstrung" in order to conserve space and to bring them more nearly over the center of the soundboard. Starting from the treble, or right-hand, end of the keyboard there are 60 notes with three strings each, then 18 notes with two strings each and finally, in the extreme bass, 10 notes with only one string each. Larger pianos have more strings but the same total number of notes: 88. Rectangular black objects in a row near the bottom are the heads of the dampers. Parts made of felt are in color. Strips of cloth interlaced among the strings at top damp unwanted tones from the short parts of the strings beyond the bridge (*see illustration on next page*).



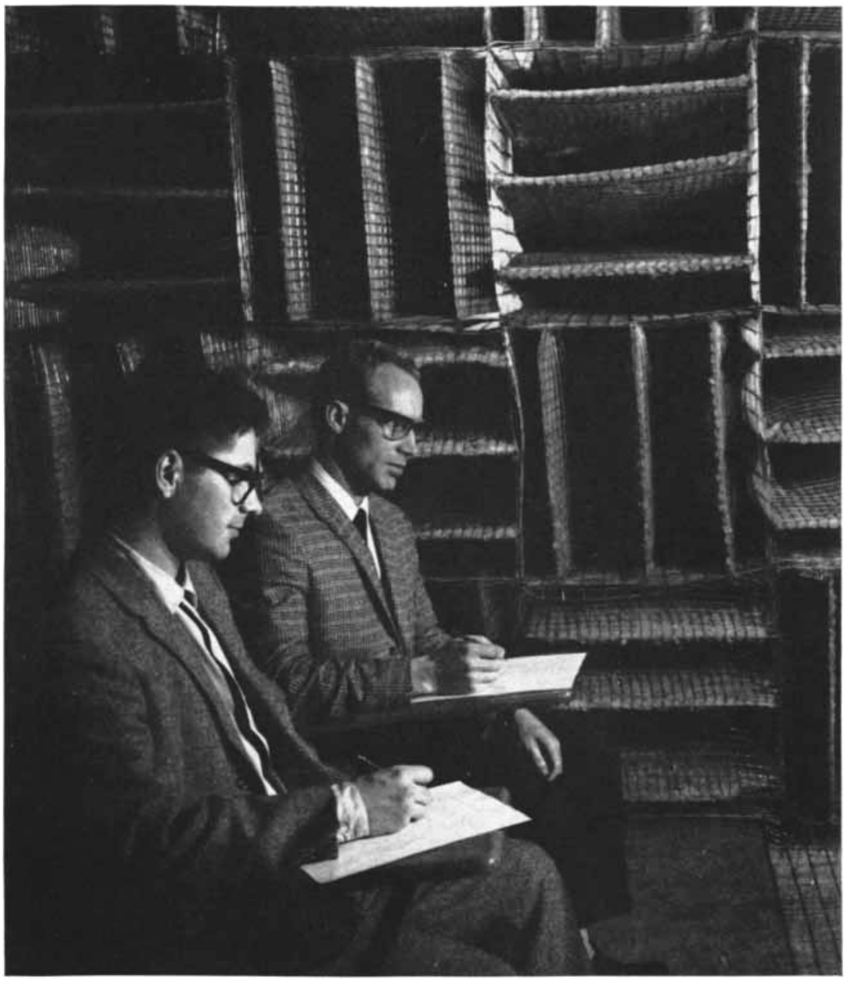
EXPLODED VIEW of the baby-grand piano depicted from above on the preceding page shows the relations of several main components. The keyboard (*bottom left*) has 88 keys divided into seven and a third octaves. Each octave has eight white keys for playing the diatonic scale (whole notes) and five raised black keys for playing the chromatic scale (whole notes plus sharps and flats). Connected to the keyboard is the action, which includes all the moving parts involved in the actual striking of the string. Three pedals (*bottom center*) serve to control the dampers in the action. When a key is struck, the hammer sets the strings in vibration and, after a very short interval known as the attack time, sound is translated by means of a wooden bridge to the soundboard, from which it is radiated into the air. During the attack time sound is also radiated to a lesser degree from both the strings and the bridge.

Several essential characteristics of the modern piano are inherited from the clavichord. The clavichord had metal strings, a percussive device for setting the strings in vibration, a damping mechanism and also an independent soundboard: the board at the bottom of the case did not also serve as the frame for mounting the strings. Moreover, although the tone of the clavichord was weak, the instrument allowed for the execution of dynamics, that is, for playing either loudly or softly.

At about the same time another forerunner of the modern piano was in process of development. In the spinet, or virginal, longer strings were introduced to produce a louder tone. Now the metal percussive device of the clavichord was no longer adequate to produce vibration in the strings. Instead the strings were set in motion by the plucking action of a quill mounted at right angles on a "jack" at the end of the key [*see lower illustration on next page*]. When the key was depressed, the jack moved upward and the quill plucked the string. When the jack dropped back, a piece of cloth attached to it damped the vibration of the string.

Around the beginning of the 16th century experiments with still longer strings and larger soundboards led to the development of the harpsichord. Although this instrument was essentially nothing more than an enlarged spinet, it incorporated several important innovations that have carried over to the modern piano. The wing-shaped case of the harpsichord is imitated by that of the grand piano. The stratagem of using more than one string per note in order to increase volume was adopted for the harpsichord by the middle of the 17th century. The harpsichord also had a "forte stop," which lifted the dampers from the strings to permit sustained tones, and a device for shifting the keyboard, both of which are preserved in the modern piano.

The invention of the piano was forecast by inherent defects in both the clavichord and the harpsichord. Neither the spinet nor the harpsichord was capable of offering the composer or performer an opportunity to execute dynamics. The clavichord, on the other hand, allowed a modest range of dynamics but could not generate a tone nearly as loud as that of the harpsichord. Attempts to install heavier strings in order to increase the volume of either instrument were futile; neither the metal percussive device of the clavichord nor the quill of the harpsichord could excite a heavy string. Moreover, the cases of these early instruments were not strong enough to sustain the increased tension of heavier strings.

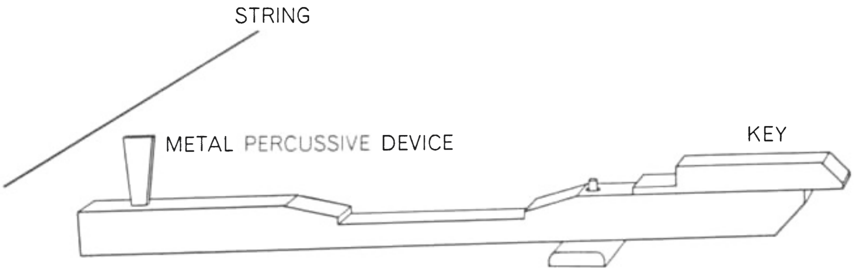


JURY composed of both musicians and nonmusicians was asked to distinguish between recordings of real piano tones and synthetic ones. When the synthetic tones were built up of harmonic partials, the musicians on the jury were able to distinguish 90 percent of these tones from real piano tones; the nonmusicians, 86 percent. When inharmonic partials were used, results showed that in most cases both the musicians and the nonmusicians were guessing; both groups identified only about 50 percent of the tones correctly. In this photograph two members of the jury are listening to tones in an anechoic, or echoless, chamber.

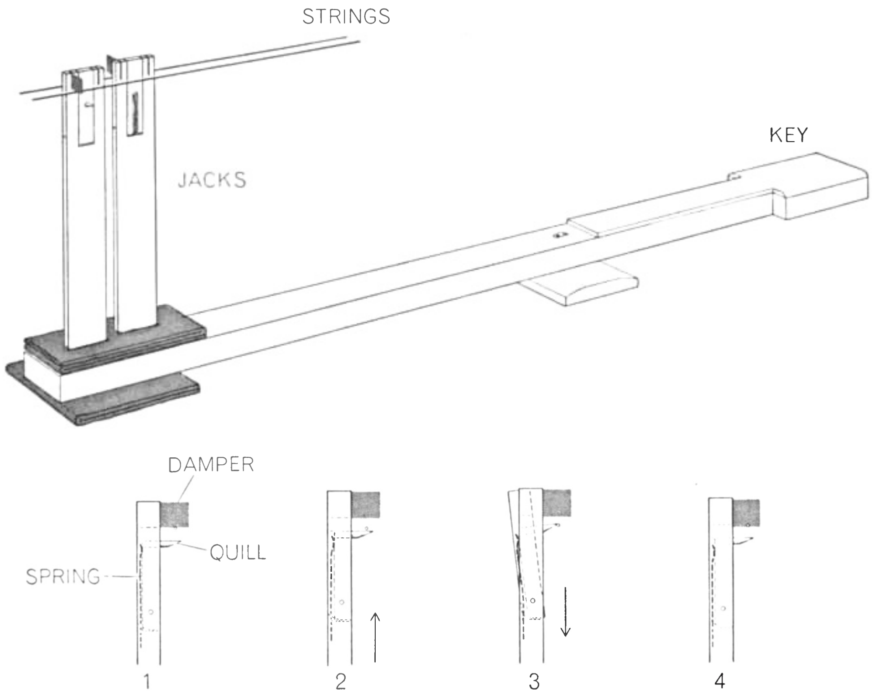
A remedy for these defects was provided by the Italian harpsichord-maker Bartolommeo Christofori, who in 1709 built the first hammer-action keyboard instrument. Christofori called his original instrument the "piano-forte," meaning that it could be played both softly and loudly. The idea of having the strings struck by hammers was probably suggested to him by the dulcimer, a stringed instrument played by hammers held in the hands of the performer. Christofori recognized that his new instrument would need a stronger case to withstand the increased tension of the heavier strings. By 1720 an improved model of the pianoforte included an escapement device that "threw" the free-swinging hammer upward at the string and also a back-check that regulated the hammer's downward return [*see upper illustration on page 93*]. An individual damper connected to the action of the hammer was provided for each note.

For a century and a half after Christofori's first piano appeared inventors worked to improve the new instrument, particularly its novel hammer action. Several other types of action were developed, some new and others modeled closely on Christofori's original. Pianos were built in a variety of forms: traditional wing-shaped pianos, square pianos, upright pianos and even a piano-organ combination.

Among the major innovations toward the end of this period was the full cast-



CLAVICHORD ACTION included one essential feature found in all modern pianos: a percussive device for setting the strings in vibration. A piece of metal mounted vertically at the end of the key acted both as a bridge for determining the pitch of the string and as a percussive device for producing the tone. Since one string could be used to produce more than one tone, there were usually more keys than strings. A strip of cloth was interlaced among the strings at one end to damp the tone from the shorter part of the string.



HARPSICHORD ACTION was capable of producing a louder tone than that of the clavichord, but, unlike the clavichord, it did not allow for the execution of dynamics, that is, for playing either loudly or softly. The strings were set in motion by the plucking action of a quill mounted at right angles on a "jack" at the end of the key. When the key was depressed, the jack moved upward and the quill plucked the string. When the jack dropped back, a piece of cloth attached to it damped the vibration of the string. The stratagem of using more than one string per note was adopted in the harpsichord in the 17th century.

iron frame. Constant striving for greater sonority had led to the use of very heavy strings, and the point was reached where the wooden frames of the earlier pianos could no longer withstand the tension. In 1855 the German-born American piano manufacturer Henry Steinway brought out a grand piano with a cast-iron frame that has served as a model for all subsequent piano frames. Although minor refinements are constantly being introduced, there have been no fundamental changes in the design or construction of pianos since 1855.

A part of the piano that has received a great deal of attention from acoustical physicists is the soundboard. Some early investigators believed the sound of the piano originated entirely in the soundboard and not in the strings. We now know that the sound originates in the strings; after a very short interval, called the attack time, it is translated by means of a wooden bridge to the soundboard, from which it is radiated into the air. During the attack time sound is also radiated to a lesser degree from both the strings and the bridge. In the late 19th century Frederick Mathushek and his associates proved that the quality of a piano's sound was not influenced by the transverse, or horizontal, vibrations of the soundboard. They glued together two soundboards so that the grain of one was at right angles to the grain of the other, thereby eliminating any transverse vibrations, and found that the quality of the sound was not affected by this arrangement. The behavior of the soundboard has also been analyzed theoretically by a number of eminent physicists, including Hermann von Helmholtz, but such analyses have added nothing to the principles of soundboard construction arrived at empirically by the builders of the early clavichords and harpsichords.

The development of the full cast-iron frame gave the sound of the piano much greater brilliance and power. The modern frame is cast in one piece and carries the entire tension of the strings; in a large concert-grand piano the frame weighs 400 pounds and is subjected to an average tension of 60,000 pounds. In order to maintain the tension of the strings each string is attached at the keyboard end to a separate tuning pin, which passes down through a hole in the frame and is anchored in a strong wooden pin block. Since the piano would go out of tune immediately if the tuning pins were to yield to the tremendous tension of the strings, the pin block is built up of as many as 41 cross-grained layers of hardwood.

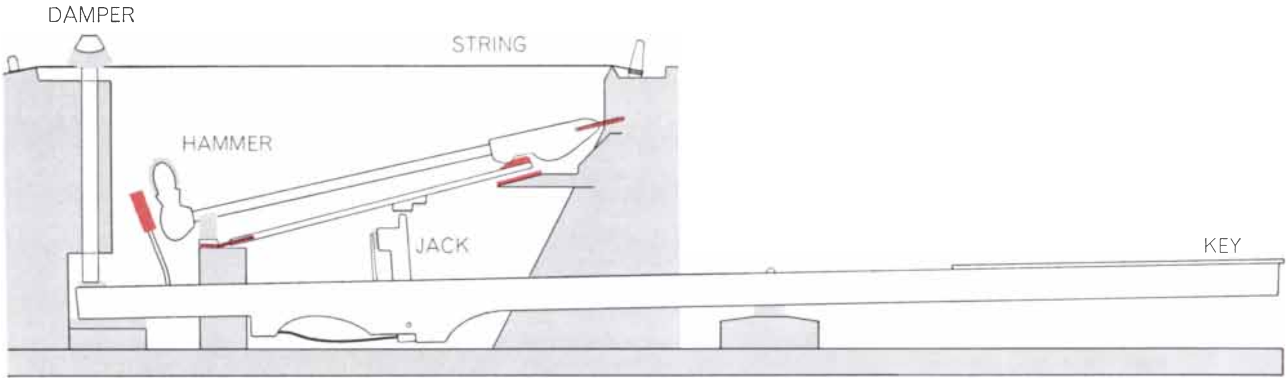
The keyboard of the modern piano is constructed on essentially the same principles that had been fully developed before the 15th century. The standard keyboard has 88 keys divided into seven and a third octaves, the first note in each octave having twice the frequency of the first note in the octave below it. Each octave has eight white keys for playing the diatonic scale (whole notes) and five raised black keys for playing the chromatic scale (whole notes plus sharps and flats). In all modern pianos the white keys are not tuned exactly to the diatonic scale but rather to the equally tempered scale, in which the octave is simply divided into 12 equal intervals.

The moving parts of the piano that are involved in the actual striking of the string are collectively called the action [*see lower illustration on opposite page*]. One contemporary piano manufacturer asserts that the action in one of his pianos has some 7,000 separate parts. Nearly all modern actions are versions of Christofori's original upward-striking ones, which took advantage of the downward force of gravity for the key's return. Some workers have experimented with downward-striking actions, so far without success.

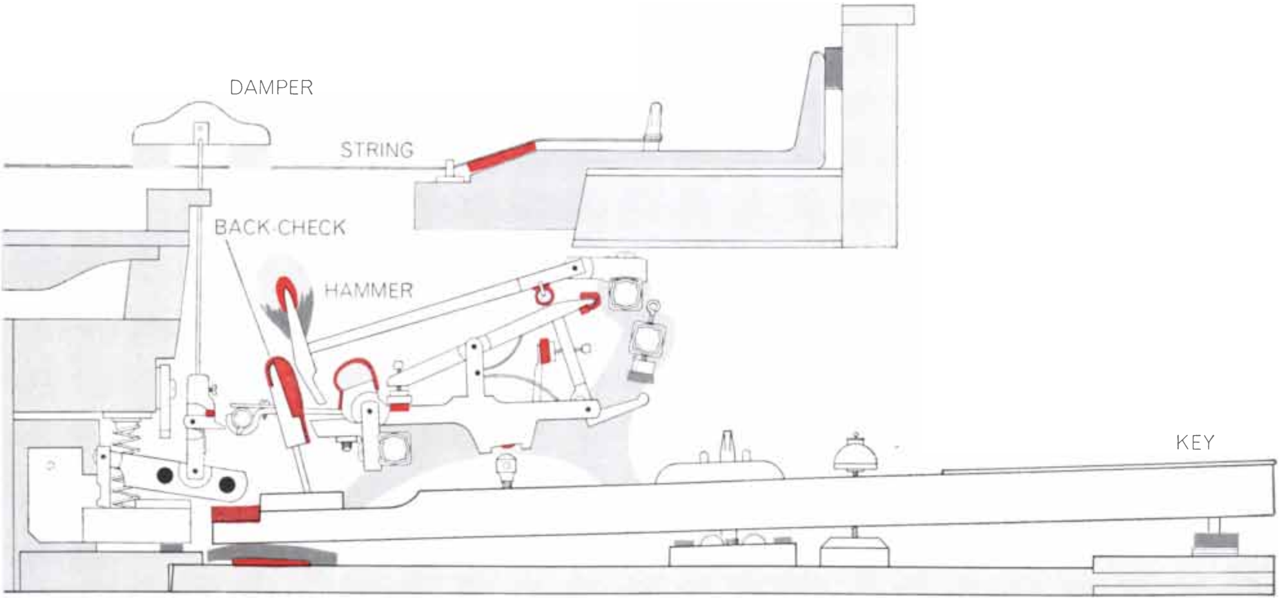
Early in the history of piano-building the hammers were small blocks of wood covered with soft leather. The inability of leather to maintain its resiliency after many successive strikings led eventually to the use of felt-covered hammers. If the felt is too hard and produces a harsh tone, it can be pricked with a needle to loosen its fibers and will produce a mellower tone. If the tone is too mellow and lacks brilliance, the felt can be filed and made harder.

A standard piano has three pedals that serve to control the dampers. The forte, or sustaining, pedal on the right disengages all the dampers so that the strings are free to vibrate until the pedal is released or the tones die away. The sostenuto pedal in the middle sustains only the tones that are played at the time the pedal is depressed; all the other tones are damped normally when their respective keys are released. The "soft" pedal on the left shifts the entire action so that the hammers strike fewer than the usual number of strings, decreasing the loudness of the instrument.

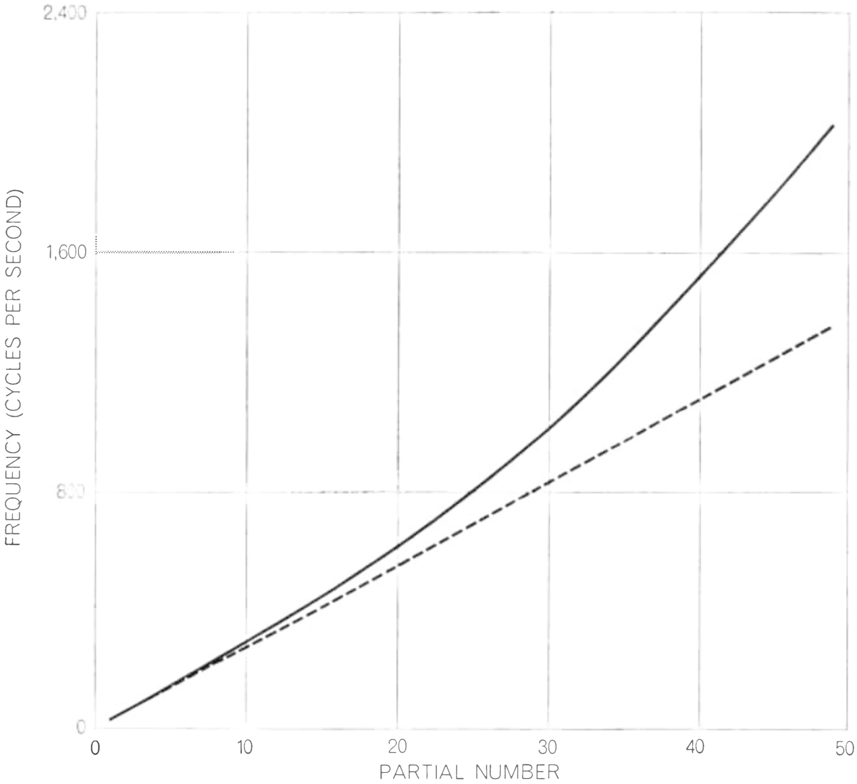
The most interesting part of the piano from the standpoint of the acoustical physicist is of course the strings. The strings used in pianos today are made of steel wire with an ultimate tensile strength of from 300,000 to 400,000 pounds per square inch. Additional weight is needed to make the bass strings vibrate slower and so generate sounds of lower pitch; this is provided by wrapping the steel wire with wire of



CHRISTOFORI ACTION, invented by Bartolommeo Christofori in the early 18th century, was the first hammer action and the prototype of all modern piano actions. It included an escapement device that "threw" the free-swinging hammer upward at the string and also a back-check that regulated the hammer's downward return. An individual damper connected to the action of the hammer was provided for each note. Christofori called his instrument the "piano-forte," meaning it could be played either softly or loudly.



MODERN PIANO ACTION is modeled closely on Christofori's original upward-striking actions, which took advantage of the downward force of gravity for the key's return. Unlike the early hammers, which were small blocks of wood covered with soft leather, the modern hammer is covered with felt. If the felt is too hard and produces a harsh tone, it can be pricked with a needle to loosen its fibers and will produce a mellower tone. If the tone is too mellow and lacks brilliance, the felt can be filed and made harder.



INHARMONICITY of a real piano tone is evident in this graph, based on data obtained from an electronic analysis of the partial tones of the lowest note on the piano keyboard (an *A*). The partials of the real piano tone (*solid line*) become increasingly sharper—that is, higher in frequency—compared with the partials of a pure harmonic tone (*broken line*).

copper or iron. Two such wrappings are often used in the extreme bass.

The vibration of a string that is attached securely at both ends is caused by a restoring force—a force that seeks to return the string to its original position after it has been displaced from that position. In a string that lacks stiffness the partial tones set up under the influence of the restoring force will be harmonic. In the piano the stiffness of the strings affects the restoring force to such a degree that some of the partials generated are not harmonic. This effect was known to Lord Rayleigh, who took it into account in formulating his classic equations for vibrating strings in the late 19th century. Many other investigators have since worked on the problem; our current effort is a continuation of the same line of inquiry.

Part of our program includes a series of tests in which a jury composed of both musicians and nonmusicians is asked to distinguish between recordings of real piano tones and synthetic ones. The synthetic tones are made by a bank of 100 audio-frequency oscillators that can be tuned to cover a range of from 50 to 15,000 cycles per second. Fine tuning is achieved by means of an attenuator connected to each oscillator circuit; the attenuator covers a range of 50 decibels, 10 decibels being a tenfold increase or decrease in the intensity of sound. With this apparatus it is possible to build up synthetic tones that represent a wide variety of partial-tone combinations. Real piano tones can be closely imitated by tuning a separate oscillator to the precise frequency and intensity associated with each partial tone of the real tone. The complex synthetic tone thus generated can then be fed into an "attack and decay" amplifier in order to give it the attack-and-decay characteristics found in the real piano tone.

In our early tests the synthetic tones were arbitrarily built up of harmonic partials. The musicians on the jury were able to distinguish 90 percent of these tones from real piano tones; the nonmusicians, 86 percent. In later tests synthetic tones built up of inharmonic partials were used. Results from these tests showed that in most cases both the musicians and the nonmusicians were guessing; both groups identified only about 50 percent of the tones correctly. Whenever a synthetic tone and a real tone were judged to be identical, we could give a description of the quality of the real tone based on our knowledge of the quality of the synthetic tone.

Recorded piano tones can also be analyzed directly by means of a conventional audio-frequency analyzer that is adjusted to pass only a narrow band of frequencies (about four cycles per second). The analyzer is set at different frequencies until it registers a maximum response for the particular partial being analyzed. A pure tone from one of the oscillators is then sent through the analyzer, and its frequency is adjusted until it gives a maximum response at the same setting as that of the real partial. An electronic counter is used to measure the frequency of the oscillator tone to an accuracy of within about a tenth of 1 percent. This frequency is assumed to be the frequency of the real partial being analyzed.

A sample of this kind of analysis for the lowest note on the piano keyboard (an *A*) is given in the illustration at the left. It is evident that the partials of the real piano tone become sharper—that is, higher in frequency—compared with the partials of a pure harmonic tone. The 16th partial, for example, is a semitone sharper—half a step higher—than it would be if it were harmonic. The 23rd partial is more than a whole tone sharp, the 33rd partial is more than two tones sharp and the highest partial in the analysis, the 49th, is 3.65 tones sharp.

In addition to the fact that the piano's tones are generally inharmonic, the partials of any particular note tend to vary considerably in loudness. This variation is called the harmonic structure of the tone, or in the case of the piano, the partial structure. One way to analyze the partial structure of a piano tone is to measure the maximum response of each partial as it passes through the audio-frequency analyzer. This method was used to obtain the partial structure of the four *G*'s shown in the illustration on the opposite page.

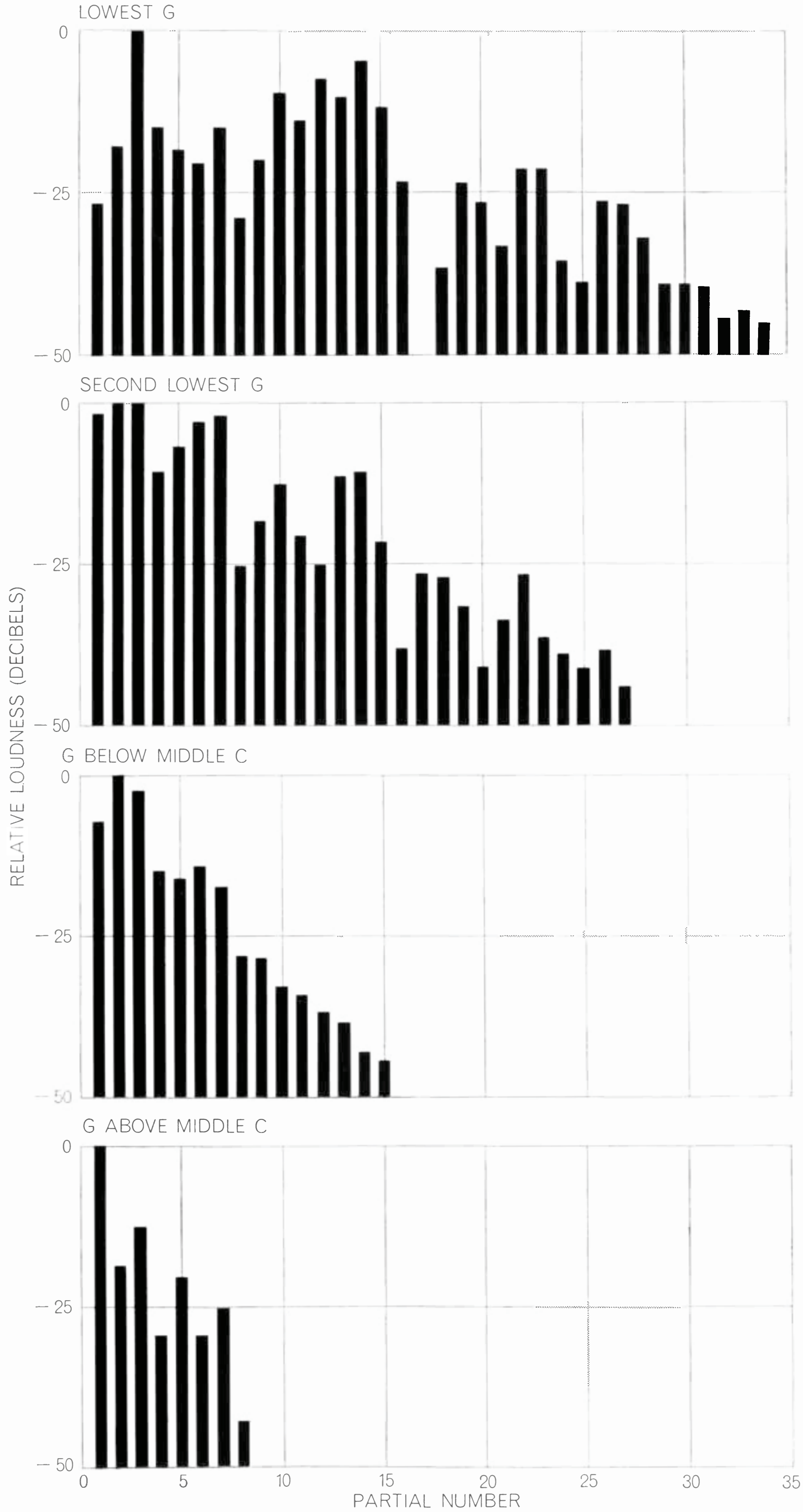
The foregoing method does not yield the most accurate description of the partial structure of a piano tone, because the structure is continuously changing. When a piano string is struck by its hammer, its response reaches a maximum an instant later. From this moment on the tone dies away as the string gradually ceases to vibrate. Because the ear perceives the entire tone dying away uniformly, it might seem that all the partials of the tone die away at an equal rate. An examination of the decay curves of individual partials proves that this is not the case [*see illustration on next page*]. It is obvious from these curves that if the partial structure of a tone were measured at any given time, it would be different from the structure at any other time. Nonetheless, some authors still refer to a decay rate of a tone as so many decibels per second. In actuality the partials do not all decay at the same rate; in some cases they may even increase in intensity before starting to decay.

The tones used for our decay-time analyses were recorded in an ordinary music studio. It was thought at first that the irregular variations during decay might be related to the acoustic characteristics of the room or the piano. Accordingly the experiment was repeated in three different rooms: a normally reverberant studio, a very reverberant room and an anechoic, or echoless, chamber. The irregularities in the decay curves were present in all three rooms [*see illustration on page 99*].

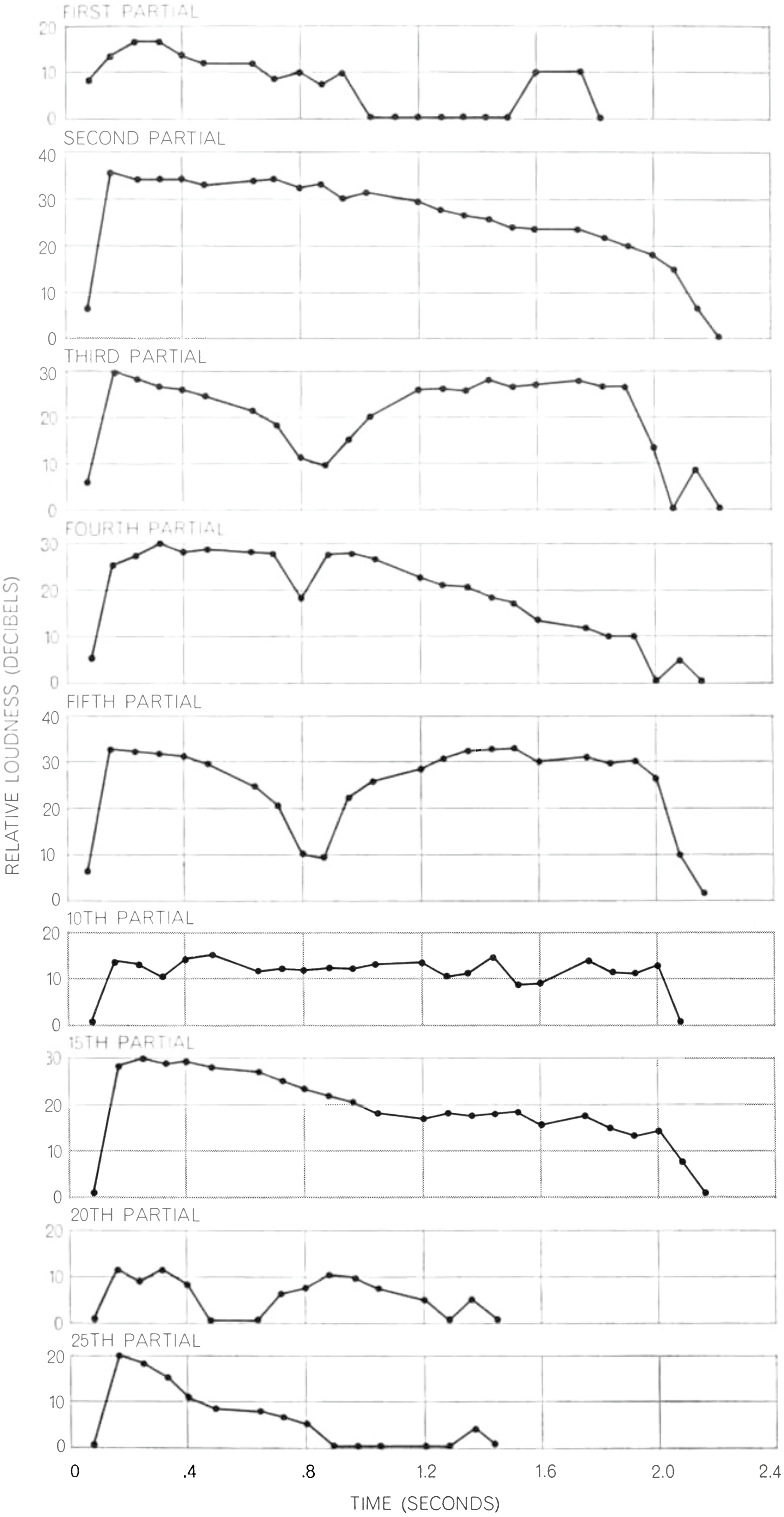
One of the main advantages of our synthetic-tone system is that it can be used to produce synthetic tones identical with one another and with a real tone except for certain selected characteristics. For example, a group of synthetic tones can be produced that differ only in attack time, the time required for the loudness of the tone to reach its first maximum after the hammer strikes the string. By presenting such a group of tones to our jury we were able to determine that for the *G* just above middle *C* the attack time has to be between zero and .05 second to sound like the *G* on a piano. An attack time in the range of from .05 to .12 second made the note seem questionable, and one longer than .12 second made it sound decidedly unlike a *G* struck on a piano. For lower notes the required attack time tended to be longer; for higher notes it tended to be shorter.

Synthetic tones can also be produced that are identical with one another and with a real tone in every respect except decay time, the time required for the string to stop vibrating after it has reached its maximum loudness. For an undamped *G* above middle *C* the decay time required for the synthetic tone to sound piano-like was between two and 5.5 seconds. Again acceptable decay times were longer for lower notes and shorter for higher notes.

Another procedure is to give synthetic tones a piano-like attack and decay but



PARTIAL STRUCTURES of the four lowest *G*'s on the piano keyboard are presented in these four bar charts. The partial structure of a musical tone is the variation in loudness of the partial tones that constitute that particular tone. The partial structures of these four notes were obtained by measuring the maximum response of each partial as it passed through an audio-frequency analyzer that was adjusted to pass only a narrow band of frequencies. The readings are given in relative decibel levels with the loudest partial of each note set at zero; the other partials can then be read as so many decibels below zero.



DECAY CURVES for nine partial tones of the lowest *C* on the keyboard demonstrate that the partial tones of a piano note do not all die away from an initial maximum at the same rate. In some cases they may even increase in loudness before beginning to decay. For each curve 30 measurements were made at equal intervals of .08 second each. Obviously the partial structure of a tone at any given time is different from the structure at any other time.

to vary the partial structure. In one test synthetic tones were built up in such a way that the loudness of each successive partial was a constant number of decibels less than that of the partial just below it in frequency. For example, if the difference was two decibels, then the second partial would be two decibels fainter than the first partial, the third partial would be four decibels fainter than the first, and so on. The limits of this "decibel difference" for obtaining a piano-like tone from the *G* above middle *C* were from five to 13 decibels per partial. In this case the acceptable range was narrower for lower notes and wider for higher notes. Tones produced when the decibel difference was below the lower limit were judged by the jury to sound "dead" or "hollow." Tones above the upper limit were described as sounding "like a harpsichord" or having "too much edge."

Synthetic tones that were built up of perfectly harmonic partials were described by the musicians and nonmusicians alike as lacking "warmth." Musicians generally use this term to suggest a certain quality of musical tone. For instance, a number of violins playing the same note at the same time produce a tone that is said to be warmer than that produced by a single violin playing alone. This quality appears to result from the fact that it is impossible for a number of musicians to play exactly in tune. When two different frequencies are sounded together, "beats" can be detected, the number of beats being equal to the difference in cycles per second between the two tones. A difference as small as two cycles per second between the fundamental frequencies of two tones can, however, produce much larger differences in the upper partials. Thus the beats that occur when two tones, each with a large number of partials, are sounded simultaneously can be quite complex. It is such beats between tones that account for the warmth produced by several violins or by a chord on the piano.

In the piano some additional warmth can be attributed to the fact that most of the hammers strike more than one string at a time. If the strings are not identically tuned, beats will occur between the high partials produced by each string. If such beats become too prominent, of course, the strings are declared to be out of tune.

The quality of a piano's tone also depends on several outside influences that

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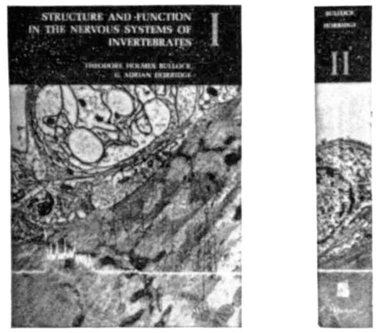

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—From a review in SCIENCE, July 23, 1965, by Dixy Lee Ray, Department of Zoology, University of Washington and Pacific Science Center, Seattle

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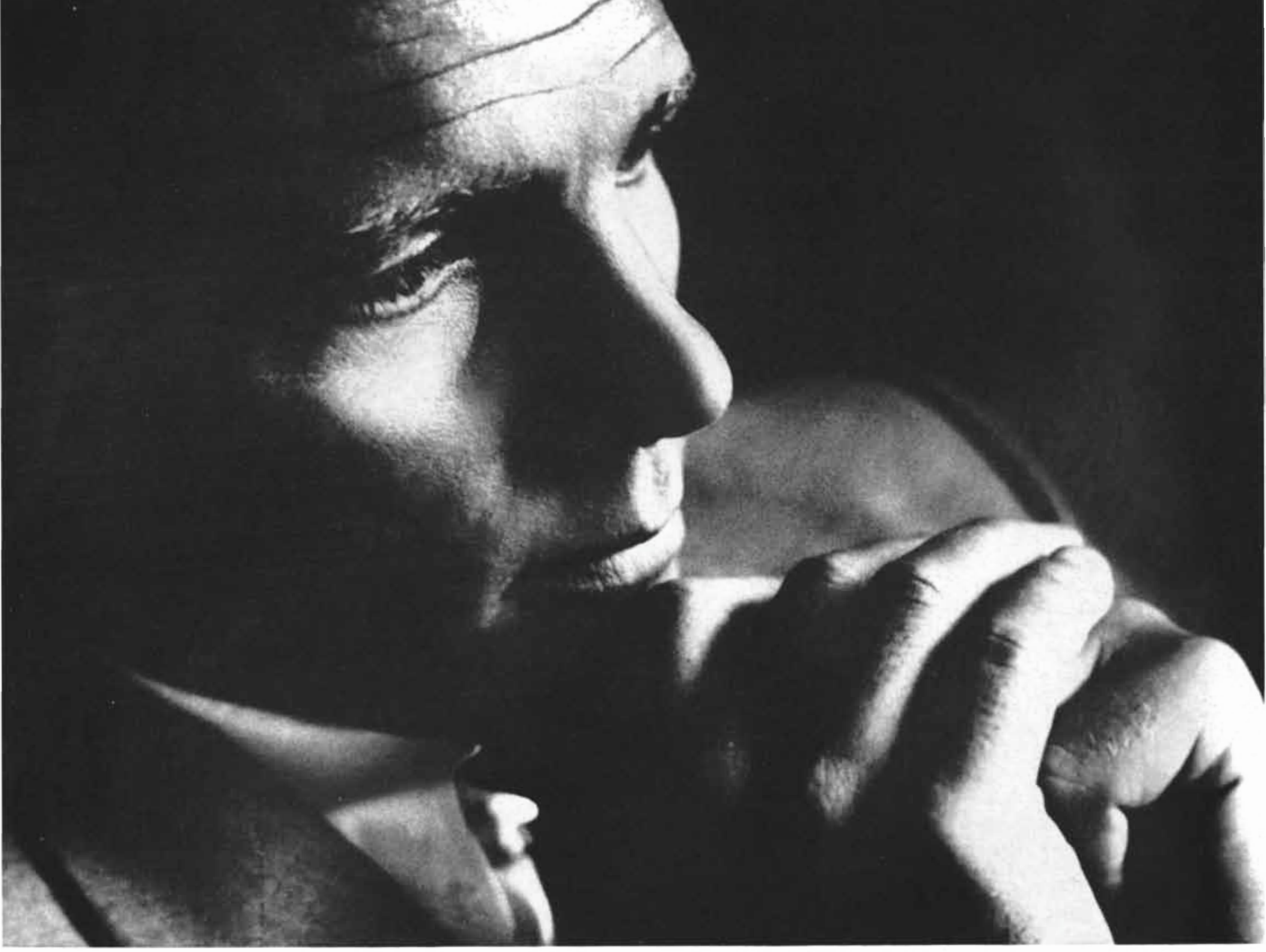

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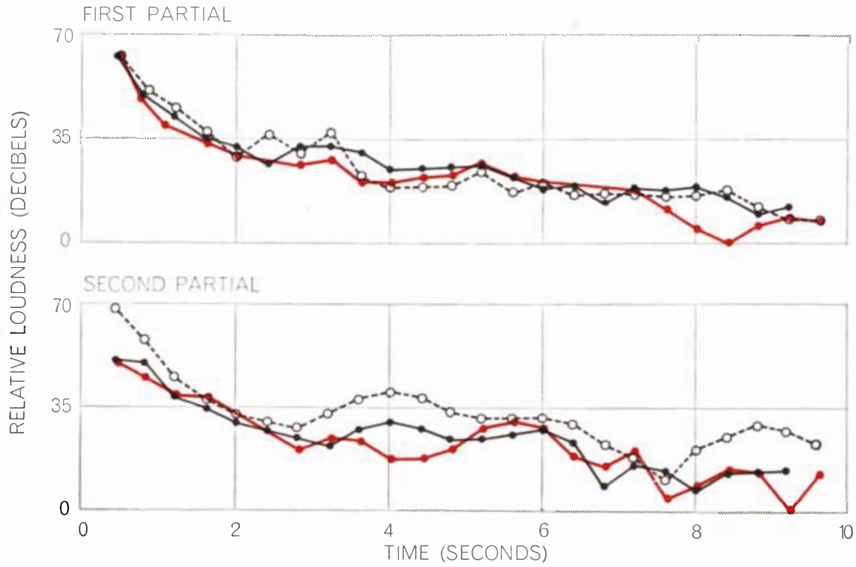

ACOUSTICS OF ROOM in which the tones used in the decay-time analyses were recorded were shown by the author and his colleagues to have a negligible effect on the irregularities present in the decay curves of different partial tones of the same note. To obtain these curves the decay times for the first and second partials of the *G* above middle *C* were recorded in three different rooms: a normally reverberant studio (*broken black curves*), a very reverberant room (*solid black curves*) and an anechoic chamber (*solid colored curves*).

are not usually considered intrinsic properties of a vibrating string. There is the impact noise of the hammer as it strikes the string, the mechanical noise of the damping pedals, the effect of the damper on the end of a tone, and the noise level of all the other strings, which are free to vibrate sympathetically when they are not damped. In early tests it became quite evident that our juries were using these factors as clues to distinguish the real tones from the synthetic ones.

The impact noise of the hammer is not as noticeable in the lower register as it is in the upper. For the high strings the impact noise is almost as loud as the tone itself. A similar noise had to be superposed on the synthetic tones before they could be effectively used in our tests. Preference tests were set up to see if piano tones without this noise were more acceptable musically than tones in which the noise was present. In general the individuals tested were satisfied with the quality of piano tones as it is, and any large departures from this quality were disparaged. Obviously this is the result of years of conditioning, of hearing piano tones produced by pianos. Some composers even write with this specific quality in mind. An example can be found in *Piano Concerto No. 2* of the American composer Edward MacDowell, in which certain passages are marked *martellato*, presumably to indicate that as much hammer noise as possible should be introduced into the passage.

The mechanical action of the pedals or dampers also makes a noise that has become part of the piano's tone. Moreover, there is a distinctive effect evident when the felt on the dampers is brought into contact with the string: the tone is not cut off cleanly but rather sounds as though it is being swallowed. The problems involved in trying to duplicate these "side effect" sounds can be eliminated by using piano tones that are produced by striking a key and allowing the sound to decay naturally by holding the key down. In this way all the other strings remain damped. The pedals are not used and only the damper of the struck string is disengaged by the action of the key.

Our studies have clearly shown that a complete description of the quality of the piano's tone must contain more than partial structure, attack time and decay time. Above all, the inharmonicity of the piano's tones must not be neglected. Some believe that the tone quality of the piano could be improved merely by making the tones more harmonic. Our tests have proved that synthetic tones built of harmonic partials lack the quality of warmth that is associated with the piano as it exists today.