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PHYSICS AND MUSIC

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PHYSICS AND MUSIC

The agreeable sound of simple melodies and Beethoven symphonies is guided by physical rules, plus a little physiology and psychology. The understanding of these principles can enhance musical creation and enjoyment

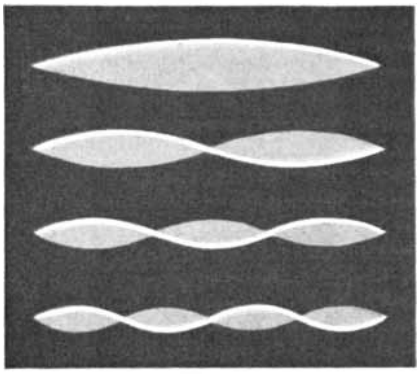
by Frederick A. Saunders

ANYONE who looks upon a great bridge arching across a wide river is thrilled by its beauty, and aware at the same time that a great deal of measuring, testing and calculating must have gone into its planning to make the structure safe. A bridge is an obvious combination of art and science. Not so obvious is the physical architecture of great music. One who listens to a symphony at an orchestral concert may know that the composer drew on his inspiration to fill pages with symbols, and that the conductor and his musicians interpret these to help bring to life again what was in the composer's mind. The listener is intellectually and emotionally moved by the sequence of sounds coming to him from many different sorts of instruments. But what has this bewilderingly complex example of art to do with science?

The answer is simple enough. Music is based on harmony, and the laws of harmony rest on physics, together with a little psychology and physiology. The simplest and most pleasant intervals of music have always existed among the harmonics of pipes and strings. From them grew the study of harmony, and they have formed the basis of many noble melodies. A classic example is the opening melody of Beethoven's *Eroica* symphony, whose first part consists of the simplest possible intervals flowing one after the other. Such simple combinations do something to our ears which is fundamentally pleasant and satisfying. Some musical instruments were well developed long before the subject of musical acoustics was born. Today the physics of music helps to guide improvements in musical instruments, in the construction of buildings with good acoustics, in the reproduction of music for immense audiences, and in many other ways.

To examine the physical basis of music we begin by considering the nature of sound. Sound is a word used in at least two senses: (1) the sensation produced in the brain by messages from the ear, and (2) the physical events outside the ear. The context usually makes it plain which meaning is intended. Thus we avoid long arguments over whether a sound can exist if there is no one present to hear it. Sound has its origin in a vibrating body, and the vibration may be *simple* or *complex*. The motion of the pendulum of a clock represents a simple vibration, one which is not rapid enough to be audible. To be heard as a musical tone, a vibration must have a frequency of at least 25 cycles per second. A pure tone is represented by a smooth curve in which distances to the right stand for time, and distances up and down correspond to the displacement of the vibrating body from its position of rest. A vibration of this sort is often called simple periodic motion because it repeats itself regularly with a constant period of time for each repetition. But pure musical tones are rare; the tones that are produced by musical instruments are almost always complex.

SYMPHONY is a vast blend of frequencies from many instruments. At left: Leopold Stokowski conducts rehearsal of New York Philharmonic.



HARMONIC series is defined in various vibrations of a string. Harmonizing frequencies are two, three, four or more times simplest vibration (*top*).

Complex vibrations can always be regarded as made up of a combination of simple vibrations of different frequencies. Their forms are very varied, as shown in the illustration on page 38. Sometime when you are out walking and have nothing better to do, try swinging your arms at different rates. The simplest case is easy: right arm going at twice the rate of the left. It is not quite so simple to make the right arm alone combine both of these motions, and it is still harder to combine rates whose ratio is one to three, two to three, and so on. One gives up before long; yet any violin string can do this easily without becoming confused. It can combine as many as 20 different rates at the same time into one complex vibration, which is caused in this case by the complicated motion of the string under the bow. These frequencies are simply related; their values are proportional to the integers 1, 2, 3, 4 and so on. They form a harmonic series. The vibration with the lowest frequency, corresponding to the number 1, is called the fundamental; the sound with double this frequency is the first harmonic, and the higher harmonics are calculated in like manner.

I. Harmonic Analyzers

The scientific study of musical instruments depends partly upon the resolution of complex tones into their harmonic elements, a process called harmonic analysis. It is often of practical importance to determine what components are present in a tone and how strong each one is. One old method of analyzing a musical tone is to study its wave form, as pictured by means of a microphone, an amplifier, and a cathode-ray oscilloscope (*see cover*). But the wave is frequently very complicated, and its analysis by mathematical methods into the simple waves of which it is built is very slow and tedious. In recent years instruments have been developed which analyze complex tones automatically, yielding rapid and accurate results.

Some of these harmonic analyzers make use of the physical effect called resonance, which is a response produced in one body from the vibration of another body. It is easily demonstrated on a piano. In piano strings the harmonics are strong. If you press gently on the key an octave below middle C, so as to free the string but not to strike it, and then strike the middle C key sharply, you will hear a continuing middle C tone coming from the lower string. The experiment succeeds only if the strings are in tune. The middle C frequency (about 260 cycles per second) is

FREQUENCY RANGE of some musical instruments and other producers of sound is tabulated in chart adapted from book *The Psychology of Music*, by C. E. Seashore. Frequencies, noted in scale at the bottom of page, are plotted horizontally. Range of scale is 40 to 20,000 cycles, as compared with the human ear's approximate range of 25 to 30,000 cycles. The thin line within each light horizontal bar indicates actual range of frequencies produced by each method. Circles on each line indicate effective range estimated by a group of expert musicians. Vertical lines at the right end of each frequency line indicate range of associated noise. The instruments in black panel are, from top to bottom, tympani, snare drum, cello, piano, bass tuba, French horn, bassoon, clarinet, male speech, female speech and jingling keys. In blue panel are cymbals, violin, trumpet, flute and clapping hands.

equal to that of the first harmonic of the lower string; hence the lower one can respond.

By a variation of the experiment, one can play a chord on a single string. Hold the lower string open as before, but now give a strong impulse to three keys at once—middle C, the C above and the G between. After the upper strings have been quieted, all three tones will be heard coming from the lower string alone, which is resonating to three frequencies at once. This works as well the other way around: hold the same three upper keys open with the right hand and give the lower C a sharp blow. The three upper tones will be heard, coming from the three untouched strings. Or again, try singing a tone into a piano with the loud pedal pressed down. (This frees the strings to vibrate in resonance with any tone with which they agree in frequency.) When you stop singing, you will hear a faint mixture of tones issuing from the piano.

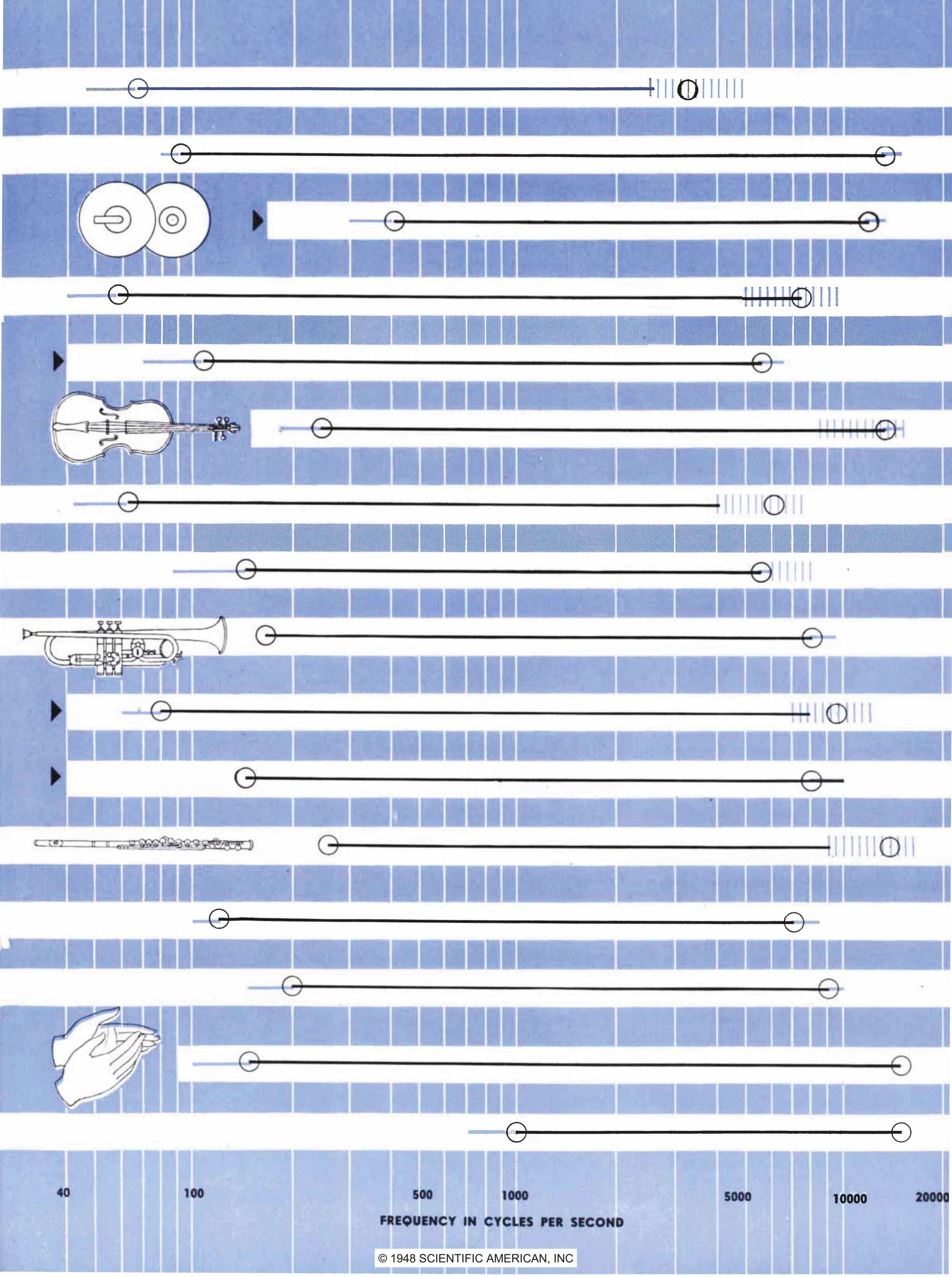
If we had some kind of attachment to the strings by means of which the response of each could be recorded, we should have one type of harmonic analyzer, but not a very good one. It would be unable to respond properly to frequencies lying between those of the strings. A more useful type of analyzer would be a single string whose pitch we could change slowly and steadily throughout the whole range of the musical scale. This could be fitted with an attachment which would record the string's responses, whenever they occurred, to the tone being analyzed. Such a device would be like the tuning apparatus in a radio receiver, which picks up radio waves on each frequency over which they are being broadcast. The device would miss nothing, but it would not be capable of making analyses instantaneously. The same sort of plan, carried out electrically, gives more rapid results. With suitable equipment it is possible to obtain within a few seconds a complete photographic analysis of a sustained tone, yielding numerical values for the strength and frequency of all harmonics present in the frequency range from 60 to 10,000 cycles per second. This method has been applied to the study of the tones of many instruments.

A remarkable frequency analyzer recently developed by R. K. Potter of the Bell Telephone Laboratories gives a continuous analysis of speech; its result is appropriately called "visible speech." One speaks into a microphone and the oscillations of his speech are then passed through 12 electrical filters, each of which allows only a narrow range of frequency to pass. When amplified. each filtered set of oscillations lights a tiny "grain-of-wheat" lamp; there are 12 lamps, arranged vertically. The fundamental tone of the speech lights one lamp, the first harmonic another farther up, and so on. The lamps that light in response to the speaker indicate the frequencies present in his speech. To reproduce his speech pattern, the light from the lamps falls on a horizontal moving belt made of phosphorescent material, so arranged that each lighted lamp traces a separate luminous line on the belt. The result is a characteristic pattern for each vowel and consonant, defined by lines of varying frequency and duration. The accompanying illustration demonstrates how a phrase looks to the eye. A trained observer can read words and phrases at sight, and a person who has been deaf from birth may thus learn to read speech. He can also correct imperfections in his own speech by matching the patterns he produces against standard ones. This visible speech is exciting to watch, and it is likely to be of great help to the deaf.

II. The Violin

Now let us turn to the consideration of musical instruments, a subject in which harmonic analysis has been very useful. We may agree at the start that nothing deserves the name of musical instrument unless it can make a loud sound. Our greatest musical artists must fill large concert halls, and for this they need loud voices, violins, pianos or other instruments. Some musical instruments require a method of amplifying the vibrations created by the player to produce powerful tones. Consider the violin as an example.

A wire mounted on a bent iron rod, with no body or plate to shake, gives almost no sound when it is excited by bow or finger. The wire is too narrow to push the air about sufficiently to create a strong sound wave. Such a performance is analogous to trying to push a

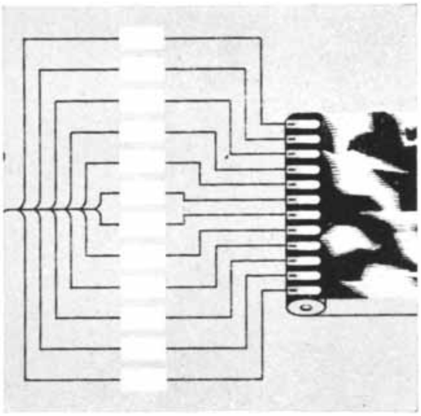

40
100
500
1000
5000
10000
20000
FREQUENCY IN CYCLES PER SECOND

canoe through the water with a round stick as a paddle. If you stretch a piece of strong twine between two hands and pluck it with a free finger, it makes very little sound. But if a part of the twine near one end is pressed on the edge of a thin board, you have a crude stringed instrument, giving a much louder sound, which now comes from the board. The sound of a violin is emitted not from the strings or the bow but from its light wooden body. The contact between the strings and the body of a violin is through the wooden bridge, which is cleverly cut to filter the sound transmitted and remove some unpleasant squeaks. To produce loud sounds, the violin body must satisfy three conditions. It must be strong, light enough to be easily shaken, and big enough to push a lot of air around when it moves. The sounding board of a piano must fulfill exactly the same conditions.

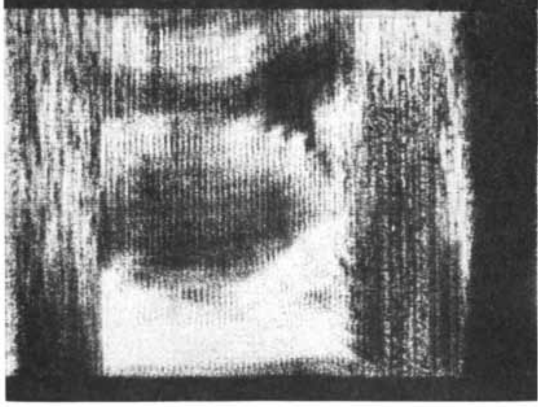
As everyone knows, stiff objects vibrate much better than limp ones; we all have observed, for instance, how noisy a job it is to wrap a parcel in stiff paper, whereas if a handkerchief is substituted for the paper there is almost no sound. Large areas of stiff paper tend to move together as one piece, and thus push on the air sufficiently to start vigorous sound waves. In a violin, the wood must be light, so that the vibrations of the strings can move it, and strong enough to sustain the tension of the strings, which adds up to about 50 pounds. The kinds of wood most used are close-grained Norway spruce for the top plate, and maple for the back.

The body of a violin should respond equally to all frequencies of vibration within its range. The fact that it fails to do this is seldom noticed. The reason for the defect will be clear if we first consider the beautiful method devised by the German acoustical physicist Ernst Chladni (at about 1800) which discloses the natural modes of vibration of plates. By sprinkling sand on a flat metal plate and drawing a rosined bow across its edge, one can get a musical tone, and some of the sand is seen to move from certain areas and some to rest along quiet "nodal" lines. The accompanying illustrations show various figures produced on violin-shaped metal plates which were fixed at both ends and at a point corresponding to the violin sound post. In each figure there are several patterns, and each pattern is associated with a tone of a particular frequency. These tones are not in a harmonic series; in fact they are usually discordant with one another. A high tone forms a pattern of many small areas; a low tone produces a few larger ones. Every violin has its own natural modes of vibration, scattered over the musical scale, and eight or ten of them may be especially strong. When a violinist produces a tone coinciding with a strong natural frequency of his instrument the violin responds loudly, but if he makes one in the range between two such frequencies, the response is poor. This unevenness in response occurs in the playing of the best artists on the best violins, but it is seldom noticed since no artist is expected to maintain an even loudness.

The number of harmonics produced, and their strength, determine the "tone color" or timbre of a sustained tone from a violin. Whenever one of the harmonics comes near one of the natural vibrations of the plates, it is increased in loudness, and the tone is changed in tone color. This happens often, because there are several natural vibrations and many harmonics in each tone. Thus the tone color varies throughout the range of the violin. No one tone color is characteristic of any violin—much less of violins of any particular age or from any one country.



ANALYZER made by Bell Laboratories separates sound frequencies with 12 filters. Each regulates a tiny light. Lights make image on screen.



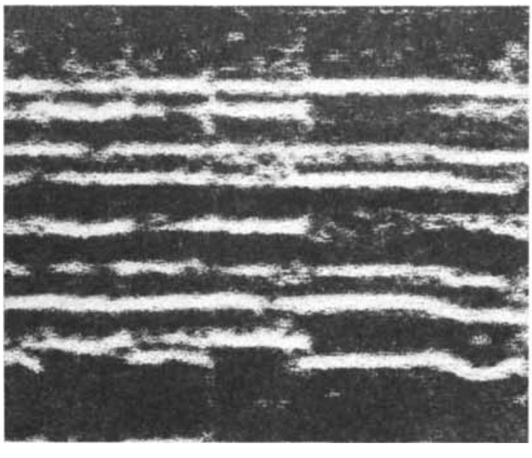
RECORD produced by "visible speech" apparatus depicted at left

As a machine for producing sound a violin is very inefficient. Most of the work done by the player in rubbing the bow against the strings is lost as heat in the wood. The Chladni patterns show another reason for inefficiency. Two adjacent areas in a plate must be moving in opposite directions when the plate vibrates, rocking back and forth with the separating nodal line at rest between them. Thus at the same instant the air is compressed by one area and expanded by the other. The net effect on the air is greatly reduced, since the contributions of the two areas nearly cancel each other. Moreover, the front and back surfaces of any plate may work against each other: while one surface compresses the air, the back of the same area starts an opposite expansion. If the two waves can meet at the edge of the plate they will partly destroy each other. This action weakens the low tones particularly, not only in violins but in pianos and loud-speakers. To prevent this effect in loud-speakers, the vibrating area is commonly set into a "baffle" which, by enlarging the surface, inhibits the meeting of the front and back waves. Larger vibrating surfaces can emit low tones better. This is why the violoncello and double bass are made progressively bigger, and why the large sounding board in a concert grand piano helps to improve its deep bass tones.

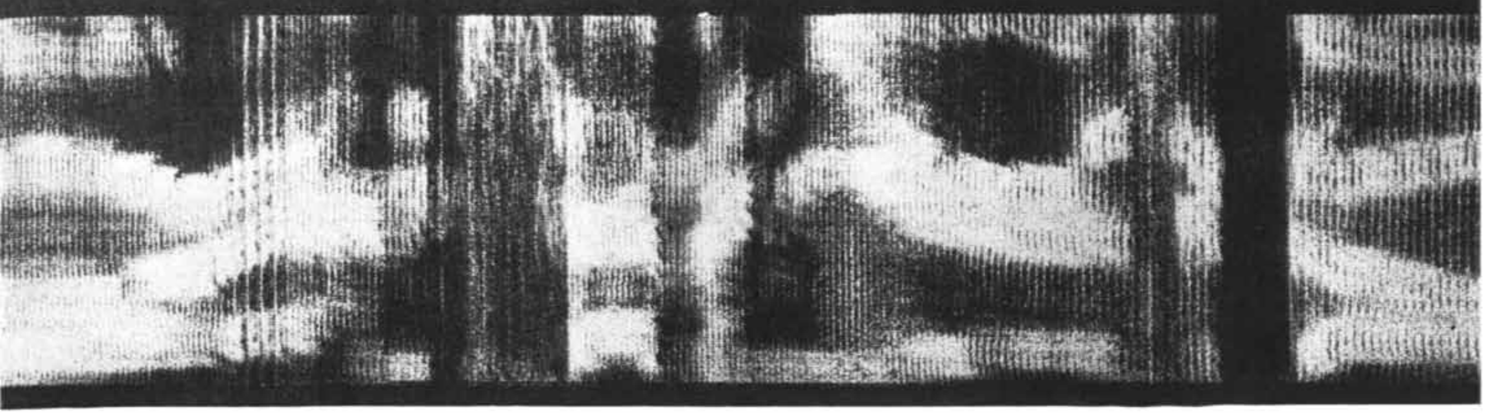
Not all of the tone emitted by a violin is produced by vibration of its plates. We must also credit the air inside the box with an important contribution. This air can vibrate in and out of the *f*-holes with a frequency which lies in the middle of the lowest octave. The tone there would be mean and ugly without the added vibration of the innner air, as one can discover by plugging the *f*-holes lightly with cotton. When the air inside the box is vibrating at or near its natural frequency, its resonance is strong. This can be demonstrated by setting a candle in front of one of the holes, with the instrument held vertical. When the right note is bowed, the flame dances wildly; for all others it remains quiet. (The effect is most marked in a cello.) Air resonance improves the tone just where improvement is most needed; that is, over a few semitones where the small size of the violin prevents the body from emitting the tones strongly. The maximum effect is near C sharp on the G string in violins, and near A or B on the G string in violas and cellos.

III. Old *v.* New Instruments

Now what makes a superlative violin?



VIOLIN MUSIC recorded by visible speech apparatus shows a horizontal



may be temporary image on a phosphorescent screen or, as in the illustration above, a pattern on a paper strip. This pattern, which may be read by a trained observer, represents phrase "Four score and seven years ago . . ."

This question is endlessly debated, but it cannot be settled by arguments. The most accurate and careful measurements in a laboratory with modern equipment are required, and a start has already been made. The impression made by a violin on a listener is due to many features: the quality or "tone color" of sustained tones, the ease with which the tones begin, the rate of decay of the sound, the loudness in different parts of the range. These items are often lumped together under the word "tone"; here we must separate them carefully. The tone color of sustained tones is probably the least important of the lot. The loudness in different ranges of pitch may be the most vital consideration in the judgment of a violin. A bad violin is weak in the low tones and too strong in the squeaky top frequencies.

Old violins are almost always thought to be better than new ones, and European better than American. This opinion may come in part from psychological causes—our admiration of old civilizations, the influence of tradition and so on—but part of it certainly comes from the beauty of workmanship characteristic of the best old instruments, and from their rarity. It is as difficult for most violinists to find any defect in a Stradivarius as it is easy for them to criticize the best-made American violin. In recent years careful experiments have been made with excellent modern apparatus, seeking to measure all the mechanical features mentioned in the preceding paragraph. A great variation in values was found among 12 Strads, many other old violins and a few dozen new ones, but the average values failed to show any consistent difference between old and new. This is not to say that there are no differences, but that the results were the same within the limits of error in the measurements, using very sensitive methods. These bold statements are supported by many "blindfold" audience tests, as well as by variations in professional opinions as to the merits of certain famous violins.

Violins seem to become lighter and better when played for a century or two. The effect of age on instruments which are not played appears to be small. Changes in the physical character of a violin can come about through vibration and also from contact with players. After a period of use a violin usually weighs more because it has absorbed water vapor from the air around the player. This makes the wood expand across the grain; when not in use it dries out again and contracts. These changes may alter both the physical and chemical properties of the wood. Some day it may be possible to attain the effects of years by a quick treatment of the wood; promising work along this line is now in progress.

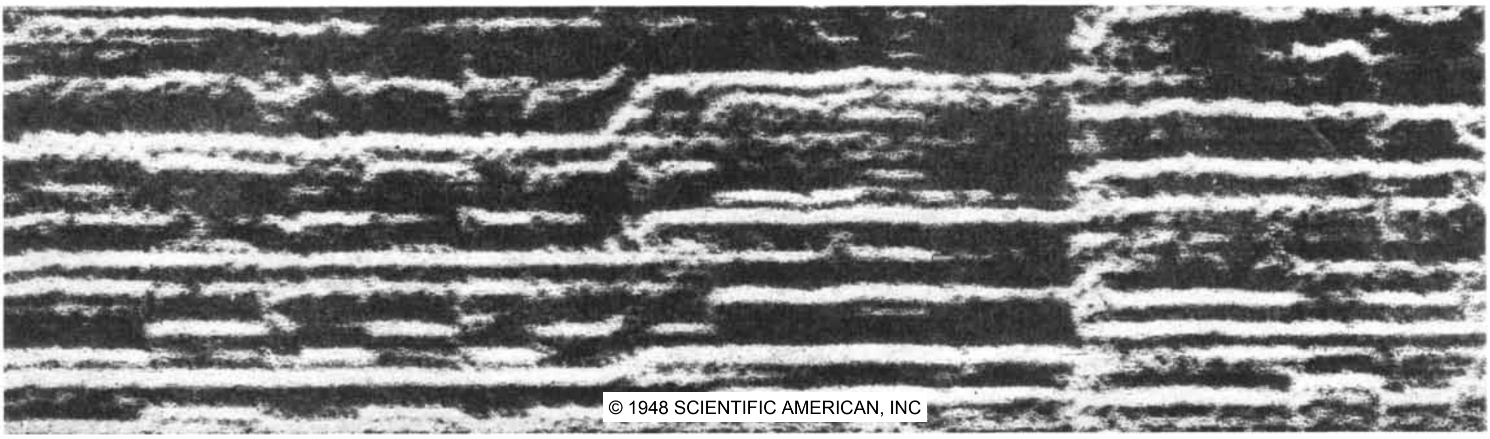
There are methods of mapping out the natural vibrations of a violin by exciting it electrically and measuring its response at every frequency. This yields a curve, called the response curve, by means of which violins can be compared. The inequalities in response at various frequencies are remarkable, in both old and new instruments. All good violins should in the future have a certified response curve furnished with them when they are offered for sale.

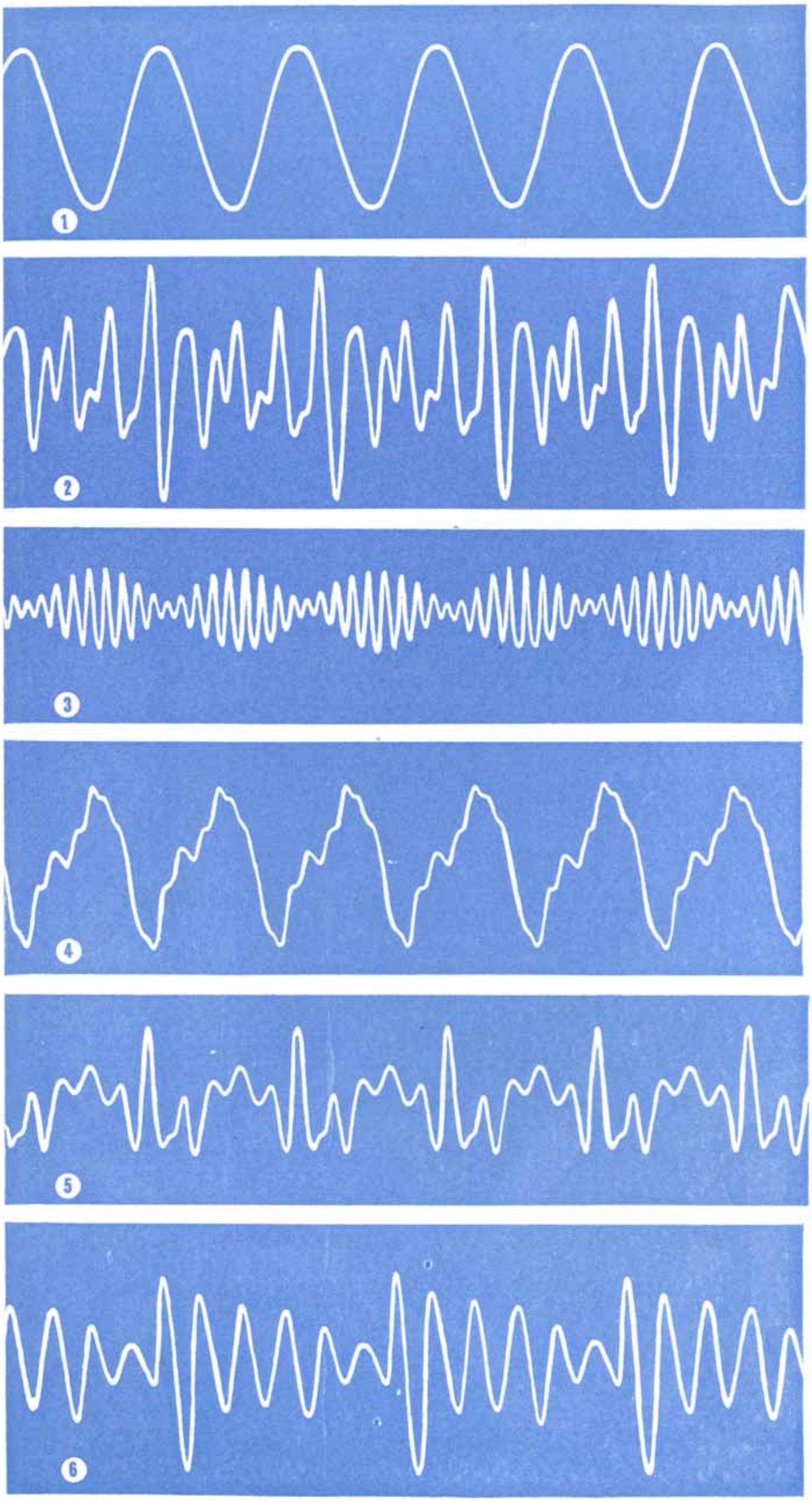
IV. The Piano

Some of the statements which I have made about the violin apply equally to the piano. The piano's sounding board acts like the violin body. While the violin has not changed in the last century, the piano has seen constant improvements in the sounding board, the strings, the hammers and the key action. So loud has the instrument become that the vibrations now shake the floor and are sometimes transmitted through the solid structure of a building to unexpected distances. In apartment houses peace may sometimes be preserved with the neighbors by placing rubber pads between the piano legs and the floor.

New problems arose with the invention of the piano's key and hammer mechanism. The hammer must be light but strong, in order to act quickly and give powerful blows to the strings. The pads must be soft to avoid the production of strong high harmonics that a hard hammer creates. (One can almost convert a piano into a harpsichord by using a teaspoon for a hammer.) When a player hits a key on the piano, the action gives the hammer a throw; at the moment when the hammer strikes a string it is not connected with the key, but is flying freely. It is as if the player were throwing soft balls at the strings from a distance. Once the hammer is on its free way, the player can do nothing more to it. His only control is

band for each harmonic produced by the instrument. Large number of bands illustrates complex nature of musical sounds. Record shows passage from Glazounov's "Concerto in A Minor," played by Jascha Heifetz.





COMPLEX WAVE FORMS of musical sounds are the result of combining several simple forms. The forms above are (1) the simple tone of a tuning fork, (2) pure chord produced by four tuning forks struck together, (3) "beat" tone of two tuning forks with almost the same frequency. Characteristic instrumental forms were made by (4) violin, (5) oboe, (6) French horn.

through the initial speed he imparts to the hammer. Thus it is a fact that for a given hammer speed the tone is exactly the same whether the key is pressed by the finger of a great artist or by the tip of an umbrella. Any skeptic to whom this statement is repulsive should open up a piano and watch the motion of a hammer. Piano "touch" is of course a mixture of effects: besides hammer speed, which affects loudness and tone color, it depends on the sequence of tones, the length of time each key is held, the management of the pedals, the phrasing and so on. Of these the last three are perhaps the most important.

There are two subjects in musical acoustics, incidentally, which often arouse furious arguments. One is piano touch. The other is the alleged characteristic flavor of music in different keys. Pupils are often taught that D major is a martial key. Today military marches are played on a piano whose D is 294 cycles per second. A musician in Mozart's time would have had a D of about 278 cycles per second (our C sharp), since the pitch has risen about a semitone in this interval. If two performances of the same music in different pitches can produce the same impression, then the flavor of the key must come from its name and not from its pitch.

V. Wind Instruments

The wind instruments operate on a very different plan from the strings, and as sound-producers they are much more efficient. A stringed instrument loses considerable energy in transmitting its vibrations from the plate to the air; in a wind instrument the sound is emitted directly by vibrations of the air inside the pipe. Hence an instrument like the oboe or clarinet in the orchestra stands out against the string section, and two or three of them are considered sufficient to balance a much larger group of violins.

The sound waves in wind instruments are generated in a variety of ways: by thin streams of air issuing from slots (the organ) or from the player's lips (flute); by the vibrations of single reeds of cane (clarinet family), of double reeds of cane (oboe family), of metal (organ), or of the player's lips (cornet, horn). Except in the case of a metal reed, which has to be tuned to its pipe, the mechanism that excites a wind instrument has no very definite natural frequency but will accommodate itself to the rate of the vibration of the air in the pipe. This rate is determined by the time it takes an exciting air impulse, traveling with the speed of sound (about 1,100 feet a second), to go down the pipe and back. In instruments which have side holes, this wave is reflected not from the end of the pipe but from the first hole that is open. By this means the player controls the effective length of the pipe and the frequency or pitch of the sound produced. Shortening the pipe by opening successive holes makes it possible to produce the notes of the musical scale; the higher tones are obtained as harmonics of these fundamental vibrations. The sound of the flute comes from two holes, the one at the mouthpiece and the first open one lower down; the vibrating air dances in and out of these two holes simultaneously. The holes still lower down emit practically no sound. The same principles apply to the oboe or clarinet except that there is no hole in the mouthpiece. The lowest tone is the only one whose sound issues from the end of the instrument.

In the brass instruments. the length of the tube is governed either by a sliding piece (slide trombone) or by insertion of additional lengths of pipe by means of valves operated with the fingers. At each length a large series of harmonics can be blown, and with several lengths available all the notes of the scale can be played, many of them in more than one way. The fundamental tones are not often used.

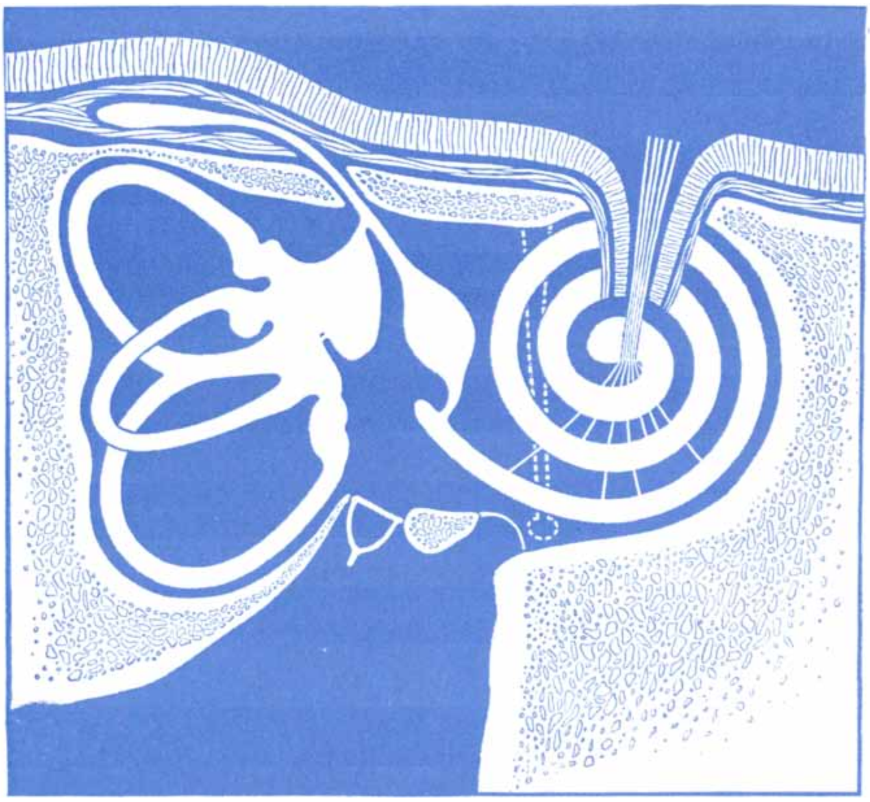
The tone colors of wind instruments are not as variable as those of violins; hence the player's opportunities for virtuosity are more limited. On the organ, the only wind instrument that has separate pipes for each pitch, the organist can build up tone colors by combining pipes of the same pitch but different colors. In the brass instruments, a player produces a marked change in tone color when he puts his fist or some other object in the "bell" from which the sound comes. This muting of the tone corresponds to what happens when one loads the bridge of a violin with an extra weight.

VI. The Singing Voice

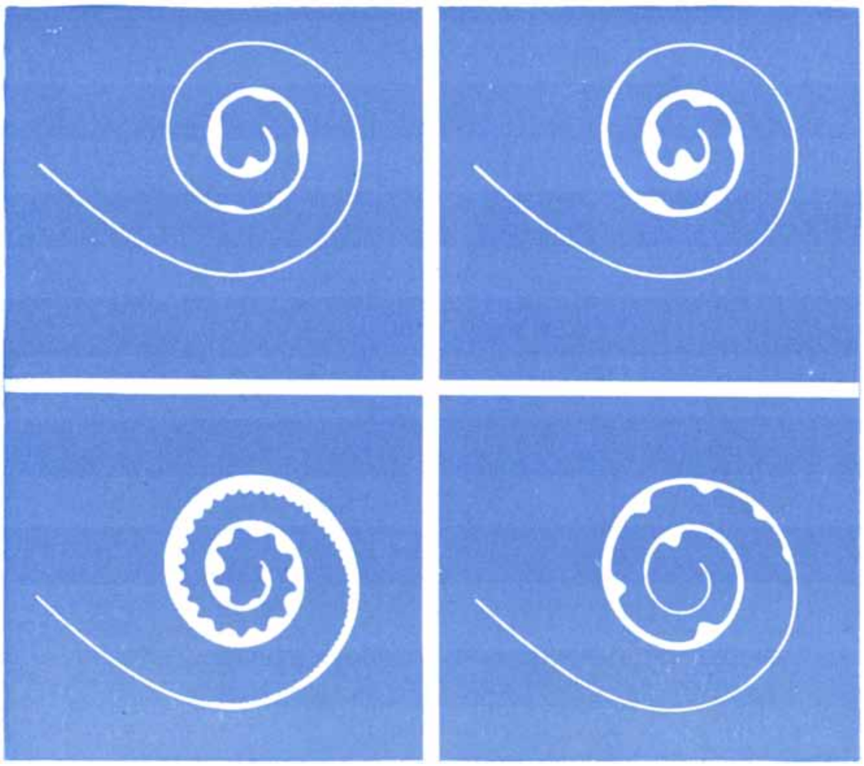
But none of these instruments has the variety of tone color available to a singer. The voice is the most versatile and expressive of all musical instruments.

The vocal cords vibrate somewhat as do the lips of a cornet player, that is, as a double reed. They produce a range of fundamental frequencies which is determined by the muscular tension that can be put on them and by their effective mass and length. The action of the cords has recently been photographed with a motion-picture camera, showing that they have a complicated, sinuous back-and-forth motion. Such a motion would be expected to generate a complex sound wave; voice sounds are indeed found to be rich in harmonics.

The throat and mouth space through which the sound passes on its way out can take the form of one chamber or be divided almost in two by the back of the tongue. A singer also varies the size of the mouth opening. These alterations enable the chamber to resonate to a variety of frequencies, some low as fundamentals, some high as harmonics. In singing, we presumably tune the chamber to resonate with the vocal cords at their fundamental



INNER EAR, here shown in highly diagrammatic drawing, is detector of sound. Spiral organ at right is the cochlea. From it run branches of the auditory nerve (*upper right*). These branches are attached to the basilar membrane, stretched across the cochlea's inside diameter along its full length. When sound vibrates membrane, nerve impulses are sent to the brain.



BASILAR MEMBRANE responds to various frequencies at various points along its length. Peaks on spiral diagrams show relative response. Two drawings at top show "false harmonics" of ear's response to a pure tone of increasing loudness. Two drawings below show membrane's accurate response to many harmonics of steamboat whistle (*left*) and note of a bugle (*right*).

or some harmonic. In general the pitch of the voice varies with the tension and length of the cords. its quality depends on the shape and size of the chamber, its loudness is determined by the amount of air pressure supplied by the lungs. The versatility of the voice comes from the ease and quickness with which all these changes can be made.

Singing teachers use certain special terms to describe all the processes involved in tone production. Although these terms have quite definite meanings to the teachers, to others such descriptions as "head tones," "chest register," and "tone placement" mean very little, and that little is probably misleading. One would suppose. for example. that the head and chest must vibrate somewhat at all times. and that the tone must always originate in the same place. One may also object to crediting the bony cavities in the head and the absorbent lung-space with helping to produce loud sounds, since these areas are powerless to contribute anything appreciable. It is to be hoped that before long there will be further experimental studies that will disclose the real behavior of the whole vocal apparatus, and that then such language can be used as will be understood by all.

VII. Musical Scales

There is one special study in which mathematics and music go hand in hand. This is in the construction of musical scales. People with unmusical ears sing up and down the range of pitches without hitting the same spot twice; but music cannot be built on this plan. The piano must have a pattern on its keyboard, and a fixed frequency for each key, as the flute has fixed positions for its side holes. The pattern of the keyboard repeats itself in each octave. An octave is measured by the first interval in the harmonic series. Two tones an octave apart have a frequency ratio of 2 to 1; they produce in our ears a simple motion and a pleasant impression. To produce a similarly pleasing effect within the octave, its intervals also should be simple. with ratios like the ones found in the harmonic series, such as the musical fifth (ratio 3 to 2) and the fourth (4 to 3). Thus the scale is built up on the plan of having as many pairs of tones as possible which please us when sounded together. At the same time the musician demands freedom to shift keys without running into any trouble with different sorts of intervals.

The final result is a scale of 12 notes with semitone intervals all exactly alike. and just filling an octave. The mathematician tells us that if we multiply the frequency of any starting note by the 12th root of two (or 1.05946), we obtain the frequency of the next higher note, and if we continue this process. after 12 multiplications we arrive at the beginning of the next octave. This scale does not give us perfect musical intervals inside the octave, but there seems to be no way in which we can get a better one to fit all the conditions stated. The purist objects: he has a wonderful ear and he says it hurts to hear these intervals the least bit off. So the mathematician writes another paper on a perfect—but unusable—scale.

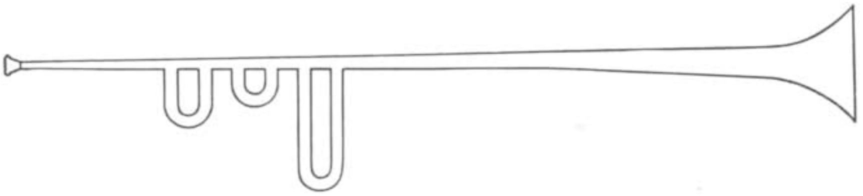
Recently the physicist and the psychologist have joined in the discussion. A new measuring device has been invented by O. L. Railsback. which he calls the chromatic stroboscope. With this he can measure the frequency of any tone while it is sounding, with a precision greater than we may ever need. It has been used to check the tuning of pianos. The results show that expert tuners agree among themselves but they tune the low notes too low and the high ones too high to fit the scale. They do this because it actually sounds better. and the explanation of this odd fact is that the harmonics of a piano string are themselves out of tune, and are sharper than they should be. The 14th harmonic occurs about where the 15th belongs. The scale that results is no longer the exact scale of "equal temperament." which we have just considered, but a "spread" one whose octave ratio is slightly greater than two to one, while its fifths are almost true. All these years we have been using two scales without knowing it. To make matters worse, it has been shown that. in contrast to the piano. the harmonics of pipes and of bowed strings are not out of tune; so that the organ is presumably tuned in equal temperament. The violin is always tuned to perfect fifths. yet nobody minds when it is played with a piano tuned to a different scale. These strange differences seem to have escaped the notice even of our friend the purist.

Recently musical psychologists of the University of Iowa, under the leadership of Dr. C. E. Seashore, have measured the performance of a number of first-class professional singers and violinists, and found that they do not use the scale of equal temperament nor any other scale exactly. We must all be less sensitive to the refinements of tuning than was supposed. The scale (or scales) we now use is quite good enough for such ears as the best of us possess.

VIII. The Listening Ear

The ear, in fact, is a surprising organ; it does not always tell the strict truth. S. S. Stevens of Harvard University has shown that the pitch of a pure tone varies with its loudness. Low tones may drop a whole tone on the musical scale, while very high tones go the other way. If, while listening to a loud tone whose pitch is off. you cover your ears, the pitch goes back to where it belongs. Fortunately, since this effect is observed to an appreciable degree only for pure tones, it is of little importance in the tones are complex. Moreover, at the pitch where the ear is most sensitive (2,000 cycles per second), the effect disappears.

The ear may even manufacture sounds that do not exist. Harvey Fletcher and his group at the Bell Telephone Laboratories have found that as the loudness of a pure tone increases. the ear begins to hear a change of tone color, seemingly caused by harmonics which appear in the tone in increasing number and strength. The tone increases in shrillness and harshness until it sounds like the blast of a cornet in one's ear. Yet an oscilloscope picture of the wave form of the sound shows no trace of these harmonics.



BRASS INSTRUMENT is stretched out to illustrate function of valves. Manipulating valves adds extra segments to effective length of pipe. This changes the rate of vibration of air in pipe and frequencies of its tones.

These ghostly harmonics arise somehow in the ear itself. The sensitive basilar membrane. where sound is detected by a series of nerve endings, has been proved to respond to different frequencies at different positions along its length. The membrane is spiral-shaped, and Fletcher pictures its "auditory patterns" by means of a set of spiral diagrams showing where disturbances occur in response to sounds of different pitch. In the case of a soft, pure tone, the membrane is disturbed only at the place appropriate to the frequency. But as the same tone grows louder, new disturbances mysteriously appear at the points where the harmonics of this tone would be recorded. The source of the false harmonics is probably traceable to a natural imperfection in the action of the mechanism of the middle ear.

A practical consequence of this quirk is that any tone, pure or complex, increases greatly in harshness as it becomes louder. Thus even a good radio gives a bad tone when turned up too loud; the ear is to be blamed, not the radio set. A violin has a harsher tone to the ear of the player than to a listener some distance away. A violin whose sound was amplified electrically to fill a large hall would sound quite unnatural.

IX. Room Acoustics

Science has made a very considerable contribution to music in connection with the acoustics of halls. To make clear the nature of this contribution we must consider some of the facts about sound in rooms. If the source of sound in a room is suddenly stopped, the sound lasts a little while; it dies down as it is absorbed or escapes through openings. The duration of this sound is long if the room is large or if the sound was a loud one; it is shortened if many absorbing substances are present. The absorptivity of a material is great if it is full of fine pores in which the regular vibrations that constitute sound are made irregular and thus turned into heat.

The best absorptive material is a closely packed audience. But porous plates of various sorts are available for covering walls or ceilings to cut down reflection of sound and increase absorption, in case the audience is not large enough. A bare room with hard walls reflects excellently, and this has two effects: the sound is made louder (just as white walls make a room lighter), and it is prolonged. Speech becomes hard to understand, because successive syllables overlap. Music usually benefits more by reflection than speech does: it has fewer short "syllables," and the reflections can make it loud enough to be heard well even in the rear seats of a very large hall.

Wallace Sabine of Harvard was the first to work out the proper way of correcting the acoustics of noisy halls by increasing their absorptivity. He founded architectural acoustics, which is fast becoming an exact science. It is now a simple matter to provide for good acoustics in a hall before it is built, and a bad hall can usually be made tolerable by treatment at any time.

One musical application of acoustics concerns the marked effect which the character of a room may have on the tone color and the loudness of a voice or other musical instrument. Most absorptive materials absorb more of the high tones than the low ones. When you select a piano in a bare showroom, it is likely to have a "brilliant" tone, meaning that it is strong in high frequencies. But if you place the same piano in a living room full of stuffed furniture, cushions and thick carpets, you may find its tone dull and weak. The high frequencies are still present, but they are quickly absorbed, and so you do not get the reinforcement of these tones that occurred in the showroom. A violin's tone color and power likewise depend on the sort of room in which it is played. On the other hand, a singer whose shrill high tones are hard to bear in an ordinary room should bring along a truckload of cushions, the presence of which would have the effect of greatly increasing the listeners' pleasure.

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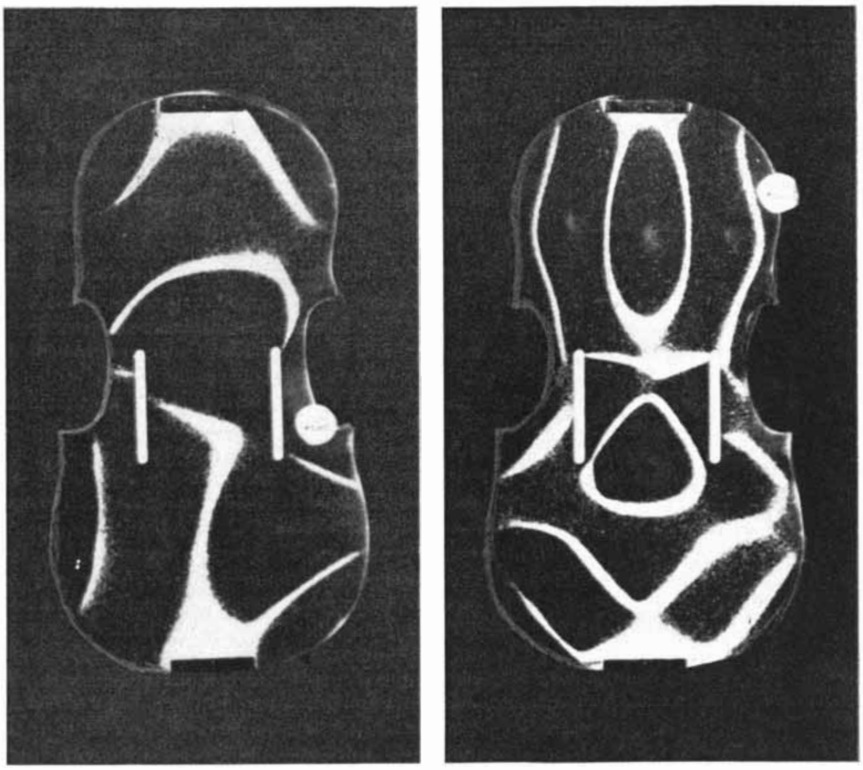

CHLADNI PLATES indicate the vibration of the body of a violin. These patterns were produced by covering a violin-shaped brass plate with sand and drawing a violin bow across its edge. When the bow caused the plate to vibrate, the sand concentrated along quiet nodes between the vibrating areas. Bowing the plate at various points, indicated by round white marker, produces different frequencies of vibration and different patterns. Low tones produce a pattern of a few large areas; high tones a pattern of many small areas. Violin bodies have a few such natural modes of vibration which tend to strengthen certain tones sounded by the strings. Poor violin bodies accentuate squeaky top notes. This sand-and-plate method of analysis was devised 150 years ago by the German acoustical physicist Ernst Chladni.