



Toward better acoustics for concert halls

Full reverberation and good spectral balance are important, but recent experiments point also to the need for directional balance—"enveloping" the listener with sound.

Manfred R. Schroeder

Concert-hall acoustics are governed by the meshing of two sets of problems: on the one hand the physical problems of wave propagation and attenuation in irregularly bounded spaces and, on the other hand, the psychological problems of how the human listener perceives the sounds impinging on his ears and what he *prefers* to hear.

In the study described in this article the acoustics of more than twenty major European concert halls were recreated in *one* location (for instantaneous comparisons) by a technique involving recording with an acoustical-

ly realistic "dummy head" (see figure 1). One of the main results of this investigation was that many concert halls need more "lateral" sound—that is, sound that arrives at the listener's head from the left or the right, rather than the front or above.

Ceilings and wall structures that scatter sound in the desired lateral directions without absorption (in effect, *reflection phase gratings*) are based on two number-theoretic concepts: quadratic residues and primitive roots. A scale model of a quadratic-residue sound scatterer is shown in figure 2.

Let us start by reviewing earlier work on reverberation and spectral balance in concert halls.

Reverberation

A few years before the turn of the century, Harvard physics professor Wallace Clement Sabine was called

upon to correct the acoustics of the newly opened Fogg Art Museum. Its auditorium, it appeared, suffered from excessive reverberation, causing speech to become largely unintelligible for all but front-row listeners.

Working long nights in the sub-basement of the Jefferson Physical Laboratory, listening to the decaying sound from organ pipes—while seated in a kind of therapeutic sweat box to minimize his absorptive presence—Sabine discovered the law named after him, the law connecting reverberation time with room volume and sound absorption. This event laid the foundations of architectural acoustics as a scientific discipline and began to rescue it from the superstitions embodied in wires stretched across cathedrals to redirect sound waves and concert-hall walls "properly aged" like a precious violin.

The practical effect of Sabine's labors

Manfred R. Schroeder is professor of physics and director of the Drittes Physikalisches Institut at the University of Göttingen, Germany. He is also associated with the Acoustics Research Center at Bell Laboratories, Murray Hill, N.J., and the Institut de Recherche et de Coordination Acoustique-Musique, Paris.

◀ **The dummy head** seen with Karl-Friedrich Siebrasse and Dieter Gottlob (contributors to work reported here) is fitted with condenser microphones and used to record sound arriving at left and right ears in selected seats of several different concert halls. Figure 1

was persuasive: Fogg Auditorium could be used again. And when Boston contemplated a new music hall, Sabine became its acoustical engineer. He analyzed such renowned halls as Carnegie in New York, Academy of Music in Philadelphia and the Gewandhaus in Leipzig—even accompanying the Boston Symphony on one of its tours—and emerged with a design that made the result, Boston Symphony Hall, one of the world's outstanding concert halls.

Sabine's formula for reverberation time T in terms of the sound absorption coefficient α can be written as follows

$$T = 13.8 \, l / c\alpha \quad (1)$$

Here l is the mean free path between successive "collisions" of a sound ray with absorbing materials and c is the velocity of sound. (The odd numerical factor 13.8 is the natural log of 10^6 and stems from the fact that Sabine's ear spanned an intensity ratio of one million to one in listening to decaying sounds in his quiet sub-basement lab.)

Curiously, Sabine¹ assumed that the mean free path l was proportional to the third root of the enclosure's volume V . In fact, it was already known from Clausius's kinetic gas theory (and even earlier from integral geometry) that, under "ergodic" conditions,²

$$l = 4V/S$$

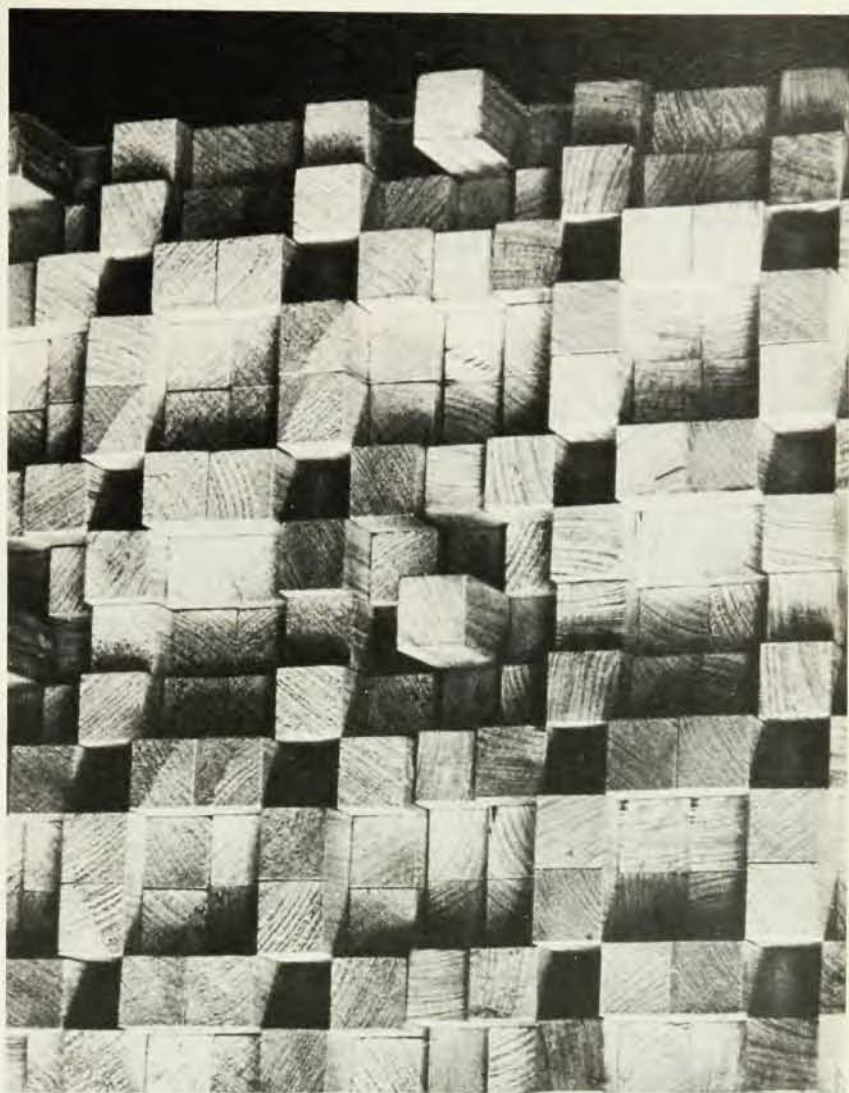
where S is the surface area of the absorber.

One problem with equation 1 is that it gives a finite reverberation time for the case of 100% absorption ($\alpha = 1$). This shortcoming was not rectified until 30 years later when K. Schuster and E. Waetzmann and Carl F. Eyring³ properly considered the essentially two-dimensional nature of surface sound absorption. This led to the formula

$$T = -13.8 \, l / c \log_e (1 - \alpha) \quad (2)$$

which agrees with equation 1 to first order in α . If the absorption was not uniform, then—on a rather ad-hoc basis— α in equation 2 was replaced by an area-weighted average. (The fact that this step can be justified theoretically, by assuming that the probabilities of sound rays colliding with different absorbers are multinomially distributed, did not emerge for another 30 years.)

Sabine's (or Eyring's) formula was accepted for acoustical designs for more than half a century. But in the early 1960's evidence began to mount that these equations could be seriously in



Wood-block model of a "quadratic-residue diffuser." Mounted on a concert hall ceiling, this device scatters sound both laterally and in the forward and backward direction. (The spacers between individual "wells" are missing in this model.) Figure 2

error. The critique converged from three sides:

► Many new halls—London's Royal Festival Hall, to mention an early prominent example—had a much "drier" (less reverberant) sound than anticipated and planned for. (See Leo Beranek's *Music, Acoustics and Architecture*⁴ for a discussion in depth of 54 of the world's major halls.)

► New precision measurement methods, employing computer-tailored test signals developed in connection with New York's Philharmonic Hall (later renamed Avery Fisher Hall), revealed that audience complaints were not subjective quirks but based in physical fact.⁵

► Theoretical considerations, aided by computer ray-tracing studies, showed that the classical reverberation-time formulas could be 50% or more off the mark and that a 20% error was not

uncommon.⁶ (A hall for symphonic music having a reverberation time of 1.5 sec instead of a planned 1.9 sec is an unmitigated disaster!)

The theoretical case against the classical formulas rests on the observation that the mean free path in general depends upon the shape of the enclosure, the distribution of the absorbers and the directivity patterns of the wall reflections (specular, diffuse, and so on). None of these effects is represented in the equations. (Nor are wave diffraction and the sound absorption in air, which depends on humidity; but these effects can be corrected within the required accuracy.)

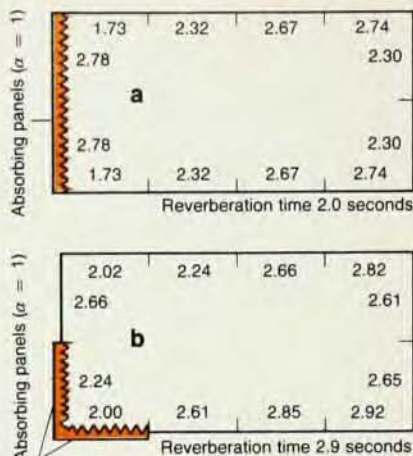
A consistent theory of reverberation, within the framework of the ray approximation, can be built on an integral equation for the sound energy flux density at the surface of the enclosure: The energy scattered from a surface

element into a given direction equals the incoming fluxes multiplied by the (angle-dependent) reflectivity integrated over all angles of incidence.⁷

Unfortunately, the resulting integral equation is not of the simple Fredholm type that yields eigenvalues from which the reverberation time could then be deduced. Rather (if we assume the sound decay to be exponential with time) the integral equation contains the unknown reverberation time *implicitly*. To circumvent this mathematical difficulty, Edgar Gilbert⁸ has supplemented the original integral equation with a second one based on the fact that the energy decay rate at any moment depends on the surface integral of incident fluxes multiplied by absorption coefficients. Of course, this integral equation contains the unknown fluxes, but both integral equations together can be solved iteratively as follows. Beginning with an (almost) arbitrary flux distribution and reverberation time, the first integral equation is used to calculate a new value of the flux distribution, and the second integral equation gives the next approximation to the reverberation time. Convergence to a stable value is usually quite fast.⁹

Figure 3 shows the result of such a calculation for a two-dimensional enclosure illustrating the importance of absorber location. With the absorption entirely on the short side, the reverberation time is 2.0 sec. By contrast, with the absorbers rearranged as shown in figure 3b, the reverberation time is 2.9 sec—a 45% increase! And the only change in the physical situation is the displacement of one absorber "panel."

The reason for this pronounced effect can be gleaned from the numbers around the perimeter representing in-



Effect of absorber configuration on reverberation time. An increase of 45% is obtained by moving one panel from its position in part a of the figure to its position in part b. Reverberation times have been calculated hereby solving the integral equations for the sound energy fluxes (the numbers around the perimeter of each rectangle). Figure 3

cident energy fluxes (in arbitrary units). In figure 3a the absorber "sees" only nonabsorbing panels; thus, the incident fluxes are high and the reverberation time correspondingly low. The absorbers are more effective, so to speak, compared to the arrangement in figure 3b where each absorbing panel "sees" the other one and thus receives a relatively low flux.

While numerical calculations of this sort can become quite complex for irregularly shaped enclosures, there is really no good reason to continue to use reverberation-time formulas that are known to be inaccurate and insensitive to important variables such as room shape and absorber location. Rather, in view of the expensive mistakes that

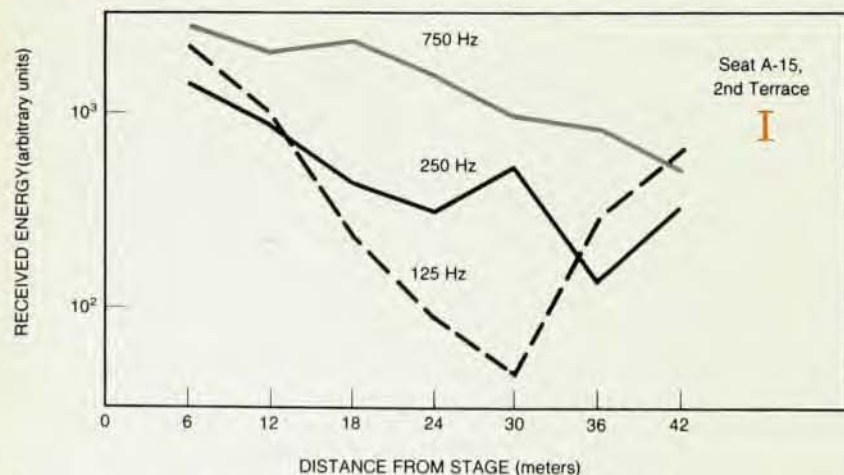
have been made in the past (and the comparative cheapness of computation, compared to the mounting cost of construction), there is every incentive for the acoustical consultant to wean himself from simple formulas and start writing sensible computer programs (some of which would fit into hand-held calculators).

Spectrum balance

Reverberation (deficient or excessive) is not the root of all evil in room acoustics. In fact, halls with nearly identical reverberation times are known that differ widely in audience acceptance. So what else could be wrong?

Obviously, there should be no disturbing echoes—habitually attracted, as if by some magnetic magic, to the ears of discriminating music critics. (I recall a case where the music critic of *The New York Times* complained of an echo in his seat; sure enough, measurements at his seat confirmed what he had perceived, but the offending echo could not be heard in any other section of the hall!)

Also, there should be no audible ventilation noise. But these are minor matters (although not always minor to correct) compared to proper "spectrum balance." If, say, the celli are playing full force in concert with a large orchestra, but you cannot hear them, something is amiss. And what is missing is probably proper low (celli) frequency transmission from the stage to the audience. This was one of the complaints in the old Philharmonic Hall at New York's Lincoln Center (prior to its rebirth as Avery Fisher Hall). Before embarking on a program of objective (physical) measurements to trace the root of the trouble, the author asked members of the Juilliard School of Music (who acted as ushers and thus knew the acoustics of the hall perhaps better than anyone else) which location, in their opinion, was the best. The answer: A-15 on the Second Terrace (give or take a row or seat). Thus, seat A-15 was included in the measurement program and, miraculously, objective measurements and subjective judgment coincided beyond expectation. (Ever since, musically trained ushers have been my preferred judges.) Figure 4 shows the energy in three different octave bands received during the first 50 msec from an impulse (a "bang") on the stage as a function of distance. Note the large spread (spectrum imbalance) particularly in the center of the main floor, at distances around 30 meters. For comparison, the much smaller energy spread at seat A-15 on the upper balcony is also shown. The deficient lower-frequency transmission from the stage to the main floor has been traced by these



Sound energy transmission from stage to main floor for New York's Philharmonic Hall in its early configuration. Note the unusually large attenuation of the lowest octave band (around 125 Hz) in the center of the main floor compared to the higher octave around 750 Hz. At seat A-15, in the second terrace, the variation of energy with frequency was much smaller; in fact, this was judged "the best seat in the house." Figure 4

measurements (using appropriate time-windows⁵) to the poor low-frequency reflectivity of the overhead acoustic panels ("clouds"). This defect has since been corrected.

Sound diffusion

So far, we have talked about essentially monaural ("monophonic") characteristics of concert-hall acoustics. But, as we know (since the commercial rise of "stereo" sound, if not before), there are also important binaural aspects of music perception.

Indeed, concert halls can be all but identical in reverberation and spectrum balance and yet differ greatly in audience acceptance.

In order to bring to light the possible causes of listener preference beyond reverberation and spectrum, my collaborators Dieter Gottlob and Karl Friederich Siebrasse¹⁰ at the University of Göttingen and I, with support from the German Science Foundation, undertook a major study of more than twenty European concert halls including such famed houses as the Grosse Musikvereinssaal in Vienna, the Amsterdam Concertgebouw and the Berlin Philharmonie.

The strategy of this investigation was as follows:

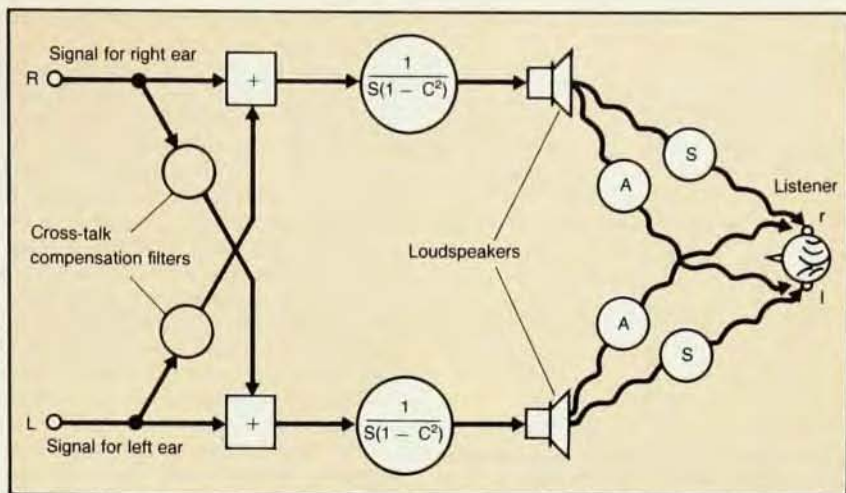
Step 1. To secure an orchestral recording of a classical symphony played in an environment free from echoes and reverberation. In the event, a multi-channel tape recording of Mozart's 41st ("Jupiter") symphony was obtained, played by one of the BBC orchestras in an anechoic room.

Step 2. To play back this tape recording over several loudspeakers located on the stage of the hall to be tested and to record the sound by means of an acoustically realistic dummy head (see figure 1) "seated" at various representative audience locations.

Step 3. To play back the dummy-head recordings to critical listeners in such a way that the acoustical signals at their ear drums approximate those of the dummy head during the recording. In other words, listeners were to be given the acoustic illusion of sitting in the tested hall at the dummy's place.

This goal cannot be accomplished by listening to the dummy-head recordings over ordinary earphones, because sounds are not properly externalized (in other words, they are heard mostly inside one's own head). Also, when the listener moves his head, the acoustic image of the orchestra moves along. Both effects are not conducive to proper concert-hall evaluation.

These effects can be avoided by radiating the two dummy-head signals from two loudspeakers placed several meters forward right and left of a listener sitting in an anechoic chamber (see the cover of this issue of PHYSICS



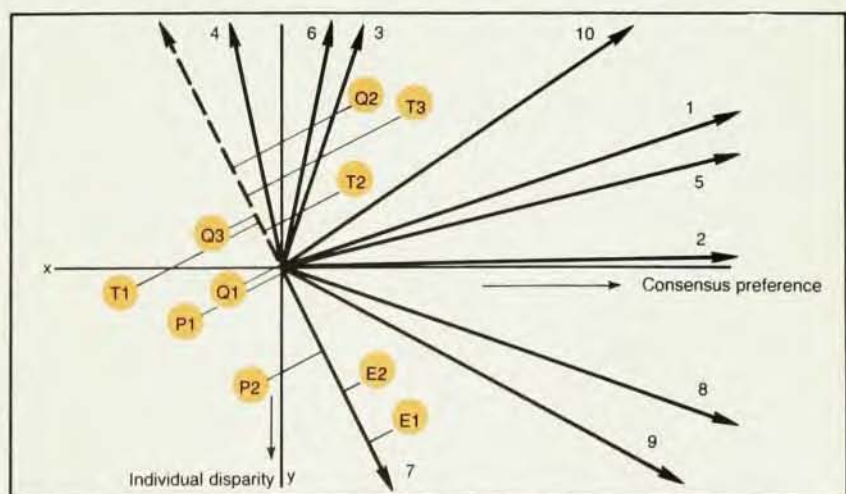
Cross-talk-compensation system that allows signals from the dummy head (L and R) to be transferred to the ears (l and r) of a human listener via two loudspeakers. The arrangement permits a sound field recorded at the dummy's ears to be realistically recreated for a listener seated in an anechoic chamber. Figure 5

TODAY). The only problem now is that sound energy from each loudspeaker reaches not only the ear for which it is intended but also the other ear on the opposite side of the listener's head. However, this "cross-talk" can be compensated by electrical filters (or equivalent computer processing). Calling the complex transmission as a function of frequency ω from a loudspeaker to the same-side ear $S(\omega)$ and that to the opposite side $A(\omega)$, then the proper cross-talk compensation filter has a frequency response $C(\omega) = -A(\omega)/S(\omega)$. The complete signal processing scheme is shown in figure 5.

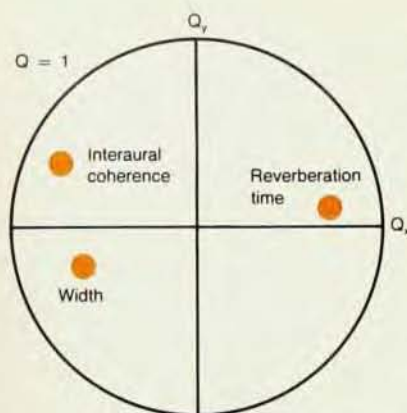
In preliminary tests of this idea we

found that echoes coming from the extreme left or right (or even from behind the listener!) were reproduced with such realism that listeners tend to turn their heads, looking for the (absent) sound source, far outside the baseline connecting the two loudspeakers. However, not unexpectedly, the illusion vanishes when the head is turned by more than ± 10 degrees, because the carefully measured transmission functions $S(\omega)$ and $A(\omega)$ only apply for a given head position and orientation.

Step 4. Using this reproduction system, the listeners were to compare two halls at a time (or two different seats in the same hall) by switching back and



Two-dimensional subjective preference space. The letter-number pairs in colored circles refer to ten different seats in four concert halls (one, two or three seats per hall). The numbered arrows represent ten different listeners. The orthogonal projection of a hall-seat point onto a particular listener's line shows its preference by that listener. Listener number 7's preferences are shown in more detail, as an example; this person likes hall-seat E1 most and hall-seat Q2 least. Greater abscissa values represent greater overall preference (because most listeners' arrows, except for number 4, point into the right halfplane). The ordinate represents individual judgment differences. Figure 6



Correlation of subjective dimensions with physical parameters. Note the strong negative correlation of interaural coherence with "consensus preference." Figure 7

forth between hall/seat "A" and "B" as often as they wished. They then had to make a preference judgment: I prefer hall "A" (or "B"). Note that this kind of test avoids all manner of ill-defined epithets such as "brilliant," "warm," "spacious" or "dull," "cold," "harsh," "dry" and so on, with which informal room acoustic judgment is "blessed".

Step 5. The important information is extracted from the preference scores by multidimensional scaling¹¹ yielding a subjective "preference space" (see figure 6). In a preference space of sufficiently high dimensionality preference scores can be represented by points (one for each measured seat) in such a way that orthogonal projections of

these points onto different directions (one for each listener) accurately represent each listener's preference score (that is, how often he preferred each hall in all of his paired comparisons combined). As described so far, the construction of a preference space (based on a mean-square error criterion) in just two or three dimensions. Thus, figure 6 shows a two-dimensional preference space (actually the two most significant dimensions of a three-dimensional preference space) for ten seats in four different halls (with reverberation times smaller than 2.2 sec) judged by ten listeners. In fact, the higher dimensions (not shown or not even calculated) contain only insignificant scatter (measurement "noise"). By contrast, the first two dimensions, x and y , in figure 6 were found to be highly reproducible and self-consistent. In particular, circular judgments ("A" better than "B", "B" better than "C" and "C" better than "A") were very rare.

From figure 6 we can see that for listener 7, for example, seat E-1 is the most preferred seat while seat Q-2 is least preferred. Conversely, listener 4 likes Q-2 most and E-1 least. The direction of the abscissa, x , in figure 6 is fixed by the convention that it accounts for the data optimally (in a mean-square error sense) on a one-dimensional scale. Since all listener directions (except 4) point into the right half-

plane, one could also label the abscissa "consensus preference": if some architectural change would move the locus of a point in figure 6 horizontally to the right, all listeners (except 4) would agree that the acoustics had improved.

The next most significant orthogonal dimension is selected as the ordinate, y , in figure 6. It reflects individual judgment disparities.

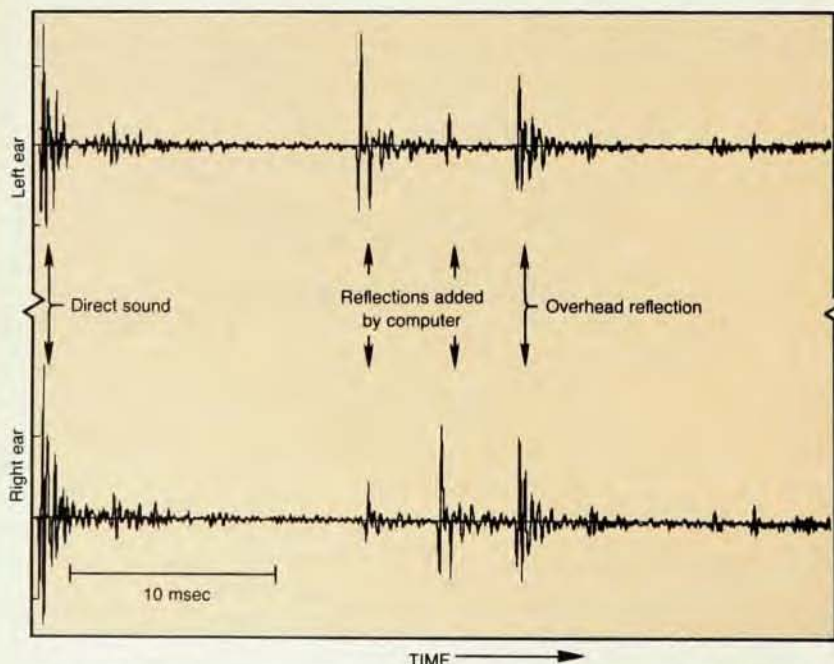
What are the physical (architectural, acoustical) facts underlying these subjective judgments? These are ferreted out by the next step.

Step 6. The subjective (x,y) values for each seat are correlated with their corresponding reverberation time values T . The resulting two correlation coefficients $\rho_{xT} = 0.76$ and $\rho_{yT} = 0.06$ are plotted as a point labelled "reverberation time" in figure 7. The location of this point, far to the right and near the abscissa, agrees with prior knowledge: reverberation time (below 2.2 sec) is strongly (and positively) correlated with subjective preference with little individual disparity.

The subjective (x,y) values for each seat are also correlated with numerous other objective parameters measured at that seat, including "interaural coherence" C . Interaural coherence is a binaural measure reflecting the similarity of the two acoustic signals at a listener's ear drums. For our purposes, we defined interaural coherence as the highest value (within a delay range of 1 msec) of the cross-correlation function of the first 80 msec of the impulse responses measured at the two ears. The measurements are made on the dummy head with an impulsive sound source at stage center.

The results of the analysis, $\rho_{xC} = -0.74$ and $\rho_{yC} = 0.32$, are plotted as the point labelled "interaural coherence" in figure 7. Its location, far to the left, means that interaural coherence is *bad* for good acoustics. Interaural coherence was the most significant parameter—on a par with reverberation time—found in our study.

Another physical measure showing strong negative correlation with consensus preference is the (average) width of a hall. In other words, wide halls—all else being equal—do not sound as well as narrow halls. Could there be a connection with the negative correlation between preference and interaural coherence? For wide halls the first strong sound rays (after the sound travelling directly from the stage to the listener's ears) arrive at a listener's ears from the ceiling. These ceiling-reflected sounds produce similar signals at the two ears (certainly much more similar ear signals as the laterally travelling sound reflected from the side walls). Thus, wider halls generally have higher interaural coherence, meaning lower preference.



Lateral reflections added (by computer) to concert-hall impulse responses (one for each ear) decrease interaural coherence. The result is an improved subjective preference. Figure 8

These conclusions have been double checked by a method called "digital modification."¹² In it the two impulse responses obtained at a dummy's head are fed into a digital computer and modified there, for example, by inserting impulses corresponding to additional lateral reflections as shown in figure 8. The music signal is then processed with the modified responses. In all such cases, consensus preference was increased. Conversely, by inserting impulses corresponding to reflections from straight ahead or overhead, subjective preference was always decreased.

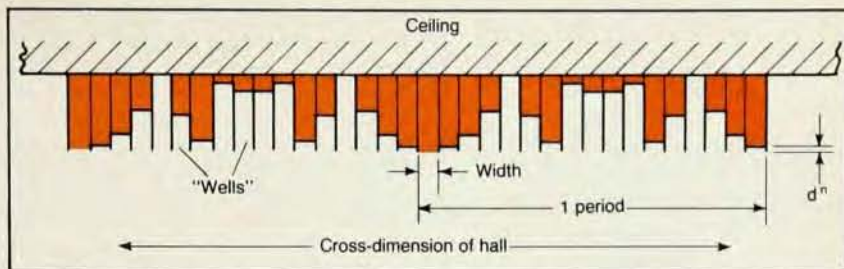
In supporting investigations, Yoichi Ando and Gottlob¹³ determined subjective preferences for nondigitally modified reverberant sound fields. They varied the direction of arrival and the delay (with respect to the sound traveling in a straight line from stage to listener) of artificially inserted reflections and measured both interaural coherence and subjective preference. The statistical correlation between the physical and subjective measure was typically -0.9 .

These findings also agree with other observations of the desirability in concert halls of early lateral reflections.^{14,15}

These results may also explain why so many modern halls have found relatively low audience acceptance. Economic constraints dictate the building of wide halls to accommodate more paying seats. In addition, modern air conditioning permits the use of relatively low ceilings compared to older auditoriums. Both of these trends of course mean more earned "dollars per cubic meter" of enclosed space—but they also increase interaural coherence resulting in lower acoustic quality.

More lateral sound

It is easy, on the computer, to modify any monaural or binaural parameter. But how can we do this in a real hall with a given ratio of height to width? Of course, one could make the ceiling suf-



A reflection phase-grating based on quadratic residues that improves lateral scatter of ceiling reflections. Figure 2 is a photograph of part of a similar but two-dimensional design carried out in wood blocks.

Figure 9

ficiently sound-absorbing that lateral energy will again predominate—as in the old-style, high-and-narrow halls. But in a large concert hall we cannot afford to waste any of the energy generated on the stage. Thus, we are forced to think of ways to redirect the sound reflected from the ceiling into a lateral pattern. This is most effectively realized by ceiling structures designed according to so-called "quadratic-residue" sequences¹⁶ (see figures 2 and 9). Such ceilings, which are in effect reflection phase-gratings, scatter incident sound over wide angles as illustrated in figure 10.

In a quadratic-residue reflection phase grating the depth d_n of the n th "well" (see figure 9) is made equal to

$$d_n = (n^2)_{\text{mod } N} \lambda_{\text{max}} / 2n$$

where $(n^2)_{\text{mod } N}$ is the remainder of n^2 modulo some prime number N . λ_{max} is the "design wavelength," the longest wavelength for which the grating will scatter efficiently.

The phase of a wavelet of wavelength λ travelling up and down one of the wells will be shifted by

$$\phi_n = -4\pi d_n / \lambda$$

Thus, the complex amplitudes of the reflected wavelets at an appropriate reference plane will be

$$a_n = \exp[-2\pi i(n^2)_{\text{mod } N} \lambda_{\text{max}} / \lambda N]$$

Taking a Kirchhoffian view of diffrac-

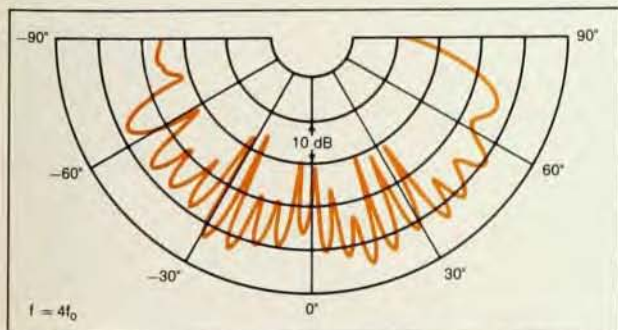
tion, we would expect the far-field to be described by the Fourier transform of the a_n . If $\lambda_{\text{max}}/\lambda$ is an integer not congruent 0 modulo N , and if n runs from $-\infty$ to $+\infty$, the answer is known from C. F. Gauss's work on quadratic residues: The spectrum is *flat*, meaning that the energies scattered into the different (discrete) directions are equal. In other words, we have realized an ideal wide-angle scatterer for a broad range of wavelengths!

An accurate theory of diffraction at reflection phase-gratings such as shown in figure 9 is of course much more complicated.¹⁷ But the accurate theory confirms the above claims and agrees well with measurements. Quadratic-residue phase gratings have also been shown to be better scatterers than random surfaces.¹⁶

Primitive roots

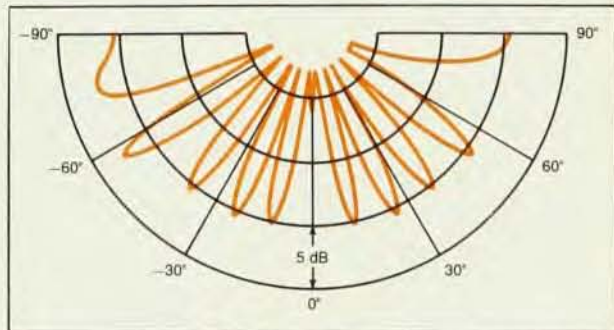
An even more effective lateral sound scatterer with reduced specular reflection can be realized by a reflection phase-grating based on "primitive roots." For example, the prime number $N = 11$ has the primitive root $g = 2$, meaning that 2^n , taken modulo 11, assumes all values 1, 2, ..., 10 exactly once as n goes from 1 to 10. In other words, $(2^n)_{\text{mod } 11}$ generates a permutation of the integers from 1 to 10. Indeed, starting with $n = 1$, one has

$$(2^n)_{\text{mod } 11} = 2, 4, 8, 5, 10, 9, 7, 3, 6, 1; \text{ etc. (repeated periodically).}$$



Energy back-scatter from a ceiling such as that shown in figures 2 and 9 for normally incident sound. Note the wide angular dispersion of reflected sound.

Figure 10



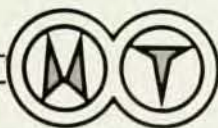
Radiation pattern of a 20-element phase array based on primitive roots. Note the near equality of individual lateral lobes and suppressed broadside lobe.

Figure 11

PREAMP- AMP- DISC



Model 509
\$325.00



- Charge Gain - 12 Volts per Picocoulomb
- Integral Linearity -0.1% to +10 Volts
- Variable Discriminator Threshold - - 100 Millivolts to 10 Volts

Mech-Tronics

NUCLEAR

430A Kay Ave., Addison, IL 60101

**For more information
WRITE OR CALL COLLECT
(312) 543-9304**

Such a permutation has an interesting and, it seems, essentially unique property: The discrete Fourier transform of the periodic sequence $\exp(2\pi i g^n/N)$ has components of equal magnitude—except for the zero-order component, which is much smaller than the others.¹⁸ Translated into reflection phase-gratings, this finding means that we can construct phase-gratings that scatter incident energy relatively uniformly into different lateral angles with relatively little energy going into the specular direction. Figure 11 shows the calculated radiation pattern of a 20-element primitive-root phase-array based on $N=11$ and $g=2$. Note the near-equality of the individual lateral radiation "lobes" and the much (10-times) smaller specular lobe at an angle of 0 degrees. However, whether primitive-root reflection phase-gratings are indeed superior to quadratic-residue designs has not yet been tested.

Both grating designs are amenable to two-dimensional generalizations if increased scatter in the forward-backward dimension, as well as lateral scatter, is desired. Figure 2 shows a scale model of such a ceiling made out of wood blocks.

Future outlook

Although interaural coherence has been established as one of the most important acoustical parameters in a quantitative way, several other problems in concert-hall acoustics remain extant—not least among them questions related to stage design and its effect upon ensemble playing. Work toward answering some of these questions is in progress.¹⁹

In addition to better architectural designs, future halls—particularly multi-purpose auditoriums—will make increasing use of electroacoustic devices. Indeed, the deficiency in low-frequency reverberation in the Royal Festival Hall mentioned above has already been corrected by "assisted resonance." Assisted resonance is a kind of negative absorption realized by numerous microphones and loudspeakers (hidden in the ceiling) connected by stabilized audio amplifiers. This daring alteration (for a major concert hall) remained officially unannounced until the audience and critics began noticing the improvement (wise public-relations strategy!).

While resistance to artificial enhancement of sound will probably remain vociferous, I believe that, before too long, we will see electroacoustic negative absorbers sprout on the walls of enclosures from living rooms to concert halls, to transform the former into the latter and the latter into acoustic cathedrals. The designation "multi-purpose auditorium" will turn from

wishful thinking to understatement. With a flick of a switch, electronically fashioned phonons will be unleashed or bridled to suit every conceivable occasion and maybe, just maybe, we will even have intelligible public-address systems.

* * *

This article is a selection and adaptation of a talk presented at the 50th Anniversary meeting of the Acoustical Society of America in Cambridge, Mass., in June 1979, and published in the Journal of the Acoustical Society of America 68, 22 (1980).

References

1. W. C. Sabine, *Collected Papers on Acoustics*, Harvard Press, Cambridge (1922); reprinted by Dover, New York (1964).
2. W. B. Joyce, *J. Acoust. Soc. Am.* **58**, 643 (1975).
3. K. Schuster, E. Waetzmann, *Ann. Phys. Leipzig* **1**, 671 (1929); C. F. Eyring, *J. Acoust. Soc. Am.* **1**, 217 (1930).
4. L. L. Beranek, *Music, Acoustics and Architecture*, Wiley, New York (1962).
5. B. S. Atal, M. R. Schroeder, G. M. Sessler, J. E. West, *J. Acoust. Soc. Am.* **40**, 428 (1966); M. R. Schroeder, B. S. Atal, G. M. Sessler, J. E. West, *J. Acoust. Soc. Am.* **40**, 434 (1966).
6. M. R. Schroeder, *Am. J. Physics* **41**, 461 (1973).
7. H. Kuttruff, *Acustica* **35**, 141 (1976); W. B. Joyce, *J. Acoust. Soc. Am.* **64**, 1429 (1978).
8. E. N. Gilbert, *J. Acoust. Soc. Am.* (to be published).
9. M. R. Schroeder, D. Hackman, *Acustica* **45**, 269 (1980).
10. M. R. Schroeder, D. Gottlob, K. F. Siebrasse, *J. Acoust. Soc. Am.* **56**, 1195 (1974).
11. J. D. Carroll, "Individual Differences and Multidimensional Scaling," in *Multidimensional Scaling: Theory and Applications in the Behavioral Sciences, Volume 1: Theory* (R. N. Shepard, A. K. Romney, S. B. Nerlove, eds.), Seminar Press, New York (1972); pages 105-155.
12. D. Gottlob, A. Kohlrausch, M. R. Schroeder, in *Fortschritte der Akustik (DAGA '78)*, VDE-Verlag, Berlin (1978); page 575.
13. Y. Ando, *J. Acoust. Soc. Am.* **62**, 1436 (1977); Y. Ando, D. Gottlob, *J. Acoust. Soc. Am.* **65**, 524 (1979).
14. A. H. Marshall, "Acoustical Determinants for the Architectural Design of Concert Halls," *Archit. Sci. Rev. (Australia)* **11**, 81 (1968); reprinted in *Benchmark Papers in Acoustics 10: Architectural Acoustics* (T. D. Northwood, ed.) Dowden, Hutchinson and Ross, Stroudsburg, Pa (1977).
15. M. Barron, *J. Sound Vib.* **15**, 475 (1971).
16. M. R. Schroeder, *J. Acoust. Soc. Am.* **65**, 958 (1979).
17. H. W. Strube, *J. Acoust. Soc. Am.* **67**, 446 and 460 (1980).
18. M. R. Schroeder, *Archiv f. Elektronik und Übertragungstechnik* **34**, 165 (1980).
19. A. H. Marshall, D. Gottlob, H. Alrut, *J. Acoust. Soc. Am.* **64**, 1437 (1978). □