and under the flight path of the aircraft, the sonic boom would be appreciably less bothersome than the sound of a subsonic jet about 1½ miles from an airport after takeoff.

2) As heard indoors by a subject under the flight path of the aircraft, the sonic boom would be about as bothersome as the sound of the subsonic jet about 1½ miles from an airport after takeoff.

3) Persons indoors not directly under the flight path of a supersonic jet but within 8 miles to either side would be bothered by the sonic boom to about the same degree as persons indoors directly under the flight path of a subsonic jet about 1½ miles from the airport would be bothered by the noise of the aircraft.

In general, one might conclude from these two studies that with the advent of the supersonic transport many more people, of the order of tens of millions (*25a*) will be exposed to a sound that is as noisy or as objectionable as that now experienced under the flight path of jet aircraft within about 1½ miles from an airport (*26*).


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# Architectural Acoustics

## Persisting uncertainties in the acoustical design of concert halls show the need for more basic research.


M. R. Schroeder


Several modern concert halls, among them La Grande Salle in Montreal, Canada, completed in 1963, and the Music Pavilion in Los Angeles, inaugurated early in 1965, have been acclaimed for their outstanding acoustical quality. Other new concert halls have been criticized for one or several acoustical deficiencies. London's Royal Festival Hall (1951), New York's Philharmonic Hall (1962), and Berlin's new Philharmonie (1963) are in this category. This inconsistency in the acoustical quality of concert halls, especially large halls of modern design, attests to an insufficient understanding of the important factors that make for good concert hall acoustics. This lack of understanding is manifest, to varying degrees, in all three problem areas affecting concert hall acoustics: the physical, the psychoacoustic, and the esthetic.

The physical side of the problem is characterized by the question, "Given an enclosure with known shape and wall materials, how do sound waves travel in it?" Much uncertainty exists about important details of the reverberation process, both as a function of time (sound decay) and as a function of location and direction (sound diffusion). In fact, even the measurement of some of the physical parameters presents formidable obstacles.

Turning to the psychoacoustic side of the problem ("Given a known sound field, what do we *hear*?"), we find that areas of uncertainty tend to dominate. Many basic questions relating, for example, to the subjectively perceptible differences of sound diffusion have not been tackled, let alone answered. More complex problems, such as the identification of the physical correlates of "reverberance" ("liveness"), "intimacy", "warmth," "immersion," and many


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other subjective categories, are much less well understood than has been generally assumed.

Finally, the esthetic or "preference" problem ("Given a known sound field and given complete knowledge of what we *can* hear, what acoustical qualities do people *prefer* to hear?") raises questions that can be investigated meaningfully only on a firm basis of physical and psychoacoustic knowledge. In addition, the preference problem is intimately related to the type of music presented: different music may call for different acoustic qualities (*1*) and, certainly, the requirements for speech differ from those for music.

Considerable, albeit insufficient, work on the physical and psychoacoustic problems has been done by a few industrial research laboratories and acoustical consultants, and by some university departments. But the remaining problems are so fundamental that only extensive research at well-staffed and well-equipped laboratories will give promise of a brighter future for architectural acoustics. It is primarily those institutions whose work does not depend on considerations of immediate gain which can afford the long-range view required for solving the exceedingly complex problems in architectural acoustics.

## Architectural Acoustics in the United States and Abroad

This country has had a fine history in architectural acoustics, beginning with Wallace Clement Sabine's work at Harvard University in the early 1900's. Sabine is regarded universally as the founder of scientific architectural acoustics. His great tradition has been continued at many places, including Harvard, the University of California at Los Angeles, the Massachusetts Institute of Technology, Brown University, Columbia University, Pennsylvania State University, Bell Telephone Laboratories, and several other industrial and consultants' laboratories.

Much of the recent progress in architectural acoustics in this country is associated with use of the digital computer (digital simulation of concert halls, computer-oriented measurement techniques, Monte Carlo computations), with reverberation theory (ray and wave statistics), with specific problems relating to transmission of sound over or through periodic surfaces (such as theater seats and panel arrays), and with subjective aspects of reverberation. A particularly noteworthy and valuable American contribution is a recent book by Leo L. Beranek (*2*), in which the world's major concert halls and opera houses are surveyed and objective criteria for future designs are proposed. Naturally, these criteria should not be considered inflexible laws but should be viewed as guideposts for future research.

Many of the experimental studies have been performed by consultants, and much new knowledge has come from industrial laboratories. However, industrial and commercial sponsorship alone does not constitute an adequate basis for sustained research in a field which is not only of considerable practical and cultural importance but is important, also, from the standpoint of human welfare.

Many significant advances in understanding and application have come from Europe (particularly Germany, Russia, Scandinavia, and Holland) and the British Commonwealth (England, Canada, and Australia). The high standing in architectural acoustics which these countries enjoy is in no small part due to the considerable government support of their university research programs.

Such support has enabled these countries to explore new principles of acoustical or electroacoustical design on a very large scale. The largest and most successful electroacoustic system for producing artificial reverberation was inaugurated 4 years ago in the Kremlin Palace of Congresses, which seats 6000 people and provides adjustable and relatively good acoustics for most locations. Another large multipurpose hall with adjustable acoustics and artificial reverberation is the new Festhalle (*3*) near Frankfurt, Germany.

A basically different kind of electroacoustic system, called "assisted resonance," was recently installed in London's Royal Festival Hall (*4*) to overcome poor response to bass tones. (The assisted resonance system provides what might be called "negative electroacoustic absorption" and allows one to alter the reverberation time for a completed hall without using microphones near the sound sources.) Many more examples of publicly supported work in architectural acoustics could be mentioned.

Regrettably, in this country there has been less government support of research in architectural acoustics. It is true that there has recently been a reactivation of research in architectural acoustics at several academic institutions—for instance at the University of California, Los Angeles, where this work is being done under the leadership of Vern O. Knudsen. If this renewed impetus is a result of the harsh lessons acoustical scientists have learned from New York's Philharmonic Hall and other new concert halls, then these experiences have, perhaps, not been in vain. But the fact remains that the support of university-based research is inadequate, in view of the many outstanding problems.

In the remainder of this article, some important research problems in architectural acoustics that are within the scope of academic laboratories are outlined.

## Reverberation Time

Reverberation time (the time required for the sound intensity in an enclosure containing no active sound sources to decay to $10^{-6}$ its original value) is the classic parameter in room acoustics. It was first measured by W. C. Sabine around 1900 at Harvard University. He measured the reverberation time for various halls by seating himself in an observation booth, sounding organ pipes, and clocking the time, with a stopwatch, at which the reverberation became inaudible. He also derived the first formula—named after him—for reverberation time as a function of absorption. It is still in use.

Since Sabine's time, considerable progress has been made both in measurement methods and in theory. As a result, it has been widely assumed that everything about reverberation time that mattered is known.

Actually, our understanding is far from complete. This is best illustrated by two halls recently opened in Europe: the concert hall of Radio Hanover and the Berlin Philharmonie. Both halls were designed to have a reverberation time of approximately 2 seconds at middle frequencies, and, according to measurements of decay rate made by the standard procedure, both came close to the design goal. But to qualified observers who have listened in both halls, the reverberation time for the Berlin hall seems to be 1.5 seconds, while that for the Hanover hall seems to be 3 seconds! Clearly, either we do not know how to measure decay rates, or we do not know what parameters other than reverberation time influence the *subjective* category of "reverberance," or our knowledge is insufficient in both areas.

Another example, better known in this country, of such a discrepancy is New York's Philharmonic Hall. The design goal was a reverberation time of about 1.9 seconds; the measured value, obtained by means of standard American and international procedures, was 2.1 seconds; the subjective impression (before alterations had been made) was a time considerably less than 2 seconds.

In the case of Philharmonic Hall, some progress has been made toward explaining the discrepancy. Computer simulation tests (*5*) have confirmed the conjecture that reverberation time defined by the *initial* rate of sound decay is better correlated with reverberance than reverberation time measured by standard methods (in which the early portion of the decay is neglected). A new method of measuring reverberation time (*6*), capable of distinguishing more precisely between initial and later rates of decay, has revealed nonlinear decays with high initial decay rates (corresponding to shorter reverberation times) for many locations in Philharmonic Hall. For most of these locations, the measurements obtained by this method and the subjectively judged reverberance are in good agreement. But there are other locations where even the most precise measurements of decay rates do not correspond to the reverberance. Thus, one is drawn to the conclusion that there are other physical parameters, in addition to decay rates, that determine reverberance. Perhaps sound diffusion and spectral balance influence the judgment. A preponderance of lateral reflections and strong low-frequency components may enhance the feeling of reverberation. But these are only speculations; only more fundamental research can answer these complex questions.

Two experimental methods seem promising for elucidating the problem of reverberance.

1) A restudy of existing halls by means of the most advanced data processing techniques and theories available. In this method, recordings of "dry" (unreverberated) speech and music are played in the hall and the reverberated signals at all locations where measurements are made are recorded. Subjective comparisons of these recordings are made, and, if possible, also comparisons of the recordings and well-defined artificial reverberation. The results of the subjective comparisons are then correlated with the measurements. The drawback of this approach is that one is limited to existing halls and their accidental admixture of parameters that may or may not be significant.

Fig. 1. Simulation of auditorium acoustics in an anechoic chamber ("free space" room). Speech and music signals are processed in a digital computer and radiated from suspended loudspeakers to create sound fields resembling those of actual auditoriums.

2) The use of simulated halls (Fig. 1), simulation being achieved electroacoustically, or by means of acoustical scale models, or by computers (in the case of computer simulation, in particular, all parameters can be altered under perfect control of the experimenter). A-B comparison tests are made, in which simulated halls having exponential decays, flat frequency response, high echo density, and complete diffusion are used as the reference standard. In this manner, all parameters can be studied in isolation or, if desired, in combination with selected other parameters. Furthermore, the influence of unknown parameters, ever present in real halls, can be excluded (or at least controlled).

New methods for multidimensional scaling of similarity and preference judgments (*7*) may be particularly useful for throwing light on the complex interaction between physical parameters and subjective impressions. In these new methods, biasing of the subject is avoided by eliciting, in paired comparison tests, judgments of similarity and expressions of preference; in earlier methods the subject was asked to make judgments concerning such ill-defined qualities as "liveness," "fullness," "presence," and "intimacy," without being given a basis of comparison. The results of the new tests, represented in a multidimensional "perceptual space," tell the experimenter which combinations of physical parameters are important and to what degree they affect subjective perception.

Similar methods can also be used to learn what the preferred reverberation times are for music of different styles (baroque, classical, romantic, and so on). An important specific question is the desirability of nonexponential sound decays for concert halls. [In experiments with computer-made artificial reverberation (*8*), a preference was sometimes found for highly nonexponential decays with decay rates corresponding to reverberation times of 4 seconds or more toward the end of the reverberation process.]

### Reverberation Theory

Reverberation theory also needs further elaboration. It was recently discovered that the three basic formulas relating reverberation time to absorption coefficients can be derived from a probabilistic equation by varying only the assumptions concerning the distribution of the numbers of reflections of sound rays from different wall sections (*9*). This discovery demonstrates the importance of probability distributions for collision frequencies, a point that has received little attention in the past (*10*).

Analysis of reverberation, based on statistical ray theory and the use of joint distribution functions for the numbers of reflections, may yield formulas for reverberation time which are applicable to a wider range of practical cases than existing formulas are. Such refined formulas are urgently needed, both for better prediction of reverberation times for concert halls and for more accurate evaluation of measurements of absorption in reverberation chambers.

### Sound Diffusion

"Sound diffusion" is defined as the distribution over the solid angle of sound energy flux. In general, it depends on location and, for transient sound signals, on time. Firm knowledge concerning sound diffusion is sparse. Not too long ago it was believed that diffusion was intimately related to the distribution of eigenfrequencies in a room. Then it was shown, both theoretically and by experiments with high-$Q$ microwave cavities, that, above 200 cycles per second, for rooms larger than 280 cubic meters (10,000 cubic feet), the eigenfrequencies are randomly distributed according to Poisson's law no matter what the diffusion (*11*). The only exceptions are rooms of perfectly regular, simple mathematical shapes (cube, hemisphere, and so on). But even in these rooms the *mode structure* (not necessarily the ray pattern) is quickly randomized by the addition of a few people or a few pieces of furniture.

Thus, the question remains, Just how much irregularity in shape is required in order for a room to have "perfect diffusion" (uniform distribution of a sound energy flux over the solid angle)? This is an important question; *perhaps* its answer will explain why some modern concert halls have relatively poor acoustics. Older halls and churches, especially of the Baroque period, usually have more irregular interior surfaces, and this irregularity may contribute to more uniform distribution of sound energy and better acoustics.

Properly shaped stage enclosures may also influence diffusion. But all this is guesswork, and much painstaking research is needed to untangle the causes of diffusion.

The effects of diffusion are even less well understood. Perhaps sound diffusion is correlated with a feeling of "immersion" in sound. There is a widespread belief that "diffusion" (meaning uniform distribution) is good for transmission of music (but not good for transmission of speech).

The measurement of diffusion also presents difficulties; the major one being that of deciding just what function of the distribution over the solid angle to measure to obtain a subjectively meaningful result. In addition, there is the purely physical problem of performing the measurement without disturbing the sound field. Large parabolic mirrors have been used, but the questions can be (and have been) asked, Does not a large mirror perturb the sound field unduly? and, What do the results mean? People do not carry large parabolic mirrors on their heads. Perhaps the ratio of lateral to vertical energies (*vertical energies* here means energies arriving from directions close to the plane normal to the axis connecting the two ears) is all that matters.

### Other Problems

There are innumerable unsolved problems, other than those connected with reverberation and diffusion, that require attention if future concert halls, opera houses, and lecture halls are to have better and predictable acoustics.

In 1963 it was discovered, in connection with measurements made in New York's Philharmonic Hall, that the "direct" sound on the main floor—that is, the sound that travels directly over the seats—was subject to large additional attenuation (up to 25 decibels) of its low-frequency content (*12, 13*). It may rightly be asked why such a pronounced effect in concert halls had not been discovered before. Part of the answer is that no other concert hall had ever been tested so extensively. More important, the methods (*14*) used in Philharmonic Hall are capable of isolating effects that are not easily analyzed by older methods. From measurements made in the hall without seats and measurements made on scale models (*13*), the effect could be attributed to a vertical "resonance" of the spaces between the rows of seats. It was also found that the attenuation of low-frequency components persists when the seats are occupied by people but that it vanishes if the floor is sufficiently "raked" (inclined upward toward the back of the auditorium).

While this example demonstrates the capabilities of modern methods of measurement and analysis, many questions remain unanswered. For example, how steep must the raking be for the attenuation of low-frequency components to be tolerable? Can a well-designed stage enclosure, providing for the arrival of sound energy at the listener's ears from above his head, help? What other methods are there of circumventing the effect?

Many acoustical scientists agree that "early" reflections (reflections having time delays that are short relative to the delays of the direct sound) are desirable for both speech and music. But how can they be provided in a large hall without introducing frequency-dependent reflections, as the panel arrays ("clouds") in Philharmonic Hall did?

For economic and other reasons, many modern concert halls, opera houses, theaters, and lecture halls have been made much larger than their predecessors. Also, the same considerations often dictate multiple use. This situation calls for amplified sound and "variable acoustics"—in other words, for electroacoustics. This field is still very much in flux, and many advances can be foreseen resulting from (i) judicious application of known techniques and (ii) development of new principles, as illustrated by the "assisted resonance" system in London's Royal Festival Hall, mentioned above.

Better cooperation between acousticians and architects is needed to solve the acoustical problems arising out of modern architectural design, with its emphasis on large unbroken surfaces which produce echoes and uneven distribution of sound. A related problem that has received little attention in this country is the design of stage sets, whose important acoustic function of reflecting sound out toward the audience is often overlooked. The problem of finding interior shapes and stage designs which are acoustically acceptable as well as pleasing to contemporary man may be insoluble, but a closer liaison between acoustician and architect is essential, if only to remind the architect that he is building not only for the eye but also for the ear.

## Noise Control

There are many challenging problems of noise control which transcend the problem of auditorium acoustics. Ironically, it was the advent of modern lightweight building materials, comparable to the old-fashioned brick wall in fire resistivity and mechanical stability (but not in sound insulation), which gave rise to much of the clamor about noise in apartments. Much progress has been made during the last decade in developing building materials and methods which provide better sound insulation. But pitifully little use has been made of these materials and methods in actual construction, especially in the construction of apartment dwellings, where the need is perhaps greatest. (Nowhere else are young families with noisy children so close to older people, who produce little noise themselves but are painfully aware of excessive noise).

Some countries, particularly Sweden and Germany, have enviable standards of noise control and sound insulation, reflected in local ordinances and national building codes (*15*). It is no secret that the United States has neglected this important legislative area; the lack of adequate legislation of this kind affects the happiness and health of our citizens, especially in urban areas and in certain industries.

The problem here is, of course, not only one of acoustics. It is in part a matter of public attitudes, and it seems that Americans (but not only Americans) have been much too lenient in this respect. "Modern" air-conditioning installations are particularly frequent offenders of our ears and may even interfere with proper speech communication, especially in many new lecture halls.

American cars, thanks to their large engines and high piston displacement, have admirably low noise outputs as compared with many of their smaller European competitors. But many of the modern consumer's other mechanical aids are noisy. The power lawnmower and the blower-cooled slide projector are two examples. These problems are not insurmountable, as has been demonstrated by a German optical firm which developed a low-voltage slide projector with a more efficient bulb requiring less cooling.

Thus, the best solutions are not always acoustical ones, but there are enough acoustical problems to make more research on sound insulation and noise control both imperative and promising.

## Appendix

Problems of scope and quality of research lead inevitably to questions concerning education. Hence, the state of formal education in all branches of acoustics is a matter of concern to all acoustical scientists. This concern led the Acoustical Society of America, which, through its meetings, its journal, and its technical committees, has fostered acoustical activities on a large scale since its founding in 1929, to request the National Science Foundation to support a Conference on Education in Acoustics. A grant for this purpose was made to the American Institute of Physics, and the conference was held, under the chairmanship of Bruce Lindsay, editor-in-chief of the *Journal of the Acoustical Society*, at the institute's headquarters in New York in March 1964.

The conference was attended by many prominent acoustical scientists from educational institutions, industry, and government. The proceedings were published in the *Journal of the Acoustical Society* (*16*).

The conference addressed itself to the problems of manpower in acoustics as they exist in industry, in government, and in colleges and universities. The conferees devoted considerable effort to an examination of the present status of the teaching of acoustics and to possible expansions and improvements. In this context, particular attention was given to the role of literature and the importance of better laboratory equipment for courses in acoustics.

As a result of the conference, the president of the Acoustical Society of America, Cyril M. Harris of Columbia University, set up a Committee on Education in Acoustics. Its chairman is Alan Powell of the David Taylor Model Basin, Washington, D.C. The committee was instructed to undertake a continuing exploration of methods of improving and expanding the teaching of acoustics at all levels, from the elementary school through the graduate school, and to examine ways of publicizing the nature of the science of acoustics and the professional opportunities in this field. Among other things, it is preparing a booklet on careers in acoustics, for distribution primarily in schools and colleges.

It was recommended by the conference that the committee explore the possibilities that would be provided by establishment of interdisciplinary programs in acoustics at universities, involving cooperative action by departments of physics, engineering, biology, psychology, oceanography, and so on, and by the establishment of acoustics as a major field of graduate study.

It was also recommended that the committee carefully consider a project for setting up, with the assistance of an appropriate government agency, one or more institutes of acoustics in major universities now having strength in acoustical research. Such institutes might combine educational and research programs in fields of outstanding need and significance, such as architectural acoustics, underwater acoustics, low-temperature acoustics, and aerodynamic acoustics.

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