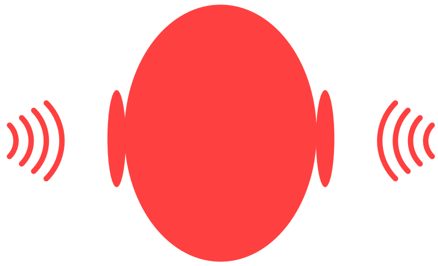

Progress in concert hall design – developing an awareness of spatial sound and learning how to control it

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For many decades, the acoustical design of rooms for music performances was driven almost exclusively by considerations of the time history of sound. However, the propagation of sound is a function of both time and space: our hearing and perception of sound are sensitive to spatial as well as temporal attributes.

This article traces the development of spatial acoustics in the design of halls during the late 20th century, in relation to the advancement of acoustical knowledge and related technologies. An outline is given of current directions in modelling and measurement systems that may lead to a greater understanding of which spatial sound fields are preferred for different events, and how the geometrical form can influence them.

1. Introduction

Over the last quarter of a century, progress has accelerated in our understanding of the effects that spatial distribution of sound have on our perception. We can consider the sound propagation in a room as the change in spatial attributes of the sound field over time, or as the change in time/frequency response over space for a given input and output. The room response is a function of space and time, and the data can be “sliced” in many different ways for our understanding of the process. This article focuses mostly on the *impulse response* of a room, i.e. the response at the output due to a given input. This is an essential part of the analysis in modelling, measurement and control.

The room response for a single-point sound source and a single-point receiver (a single ear) is called the *3D impulse response* (3DIR). This includes the effects of source and receiver directivities. It can encompass several channels of data which, together, provide complete information on the amplitude as a function of time and direction.

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The *binaural room impulse response* (BRIR) is sufficient to describe the inputs to our two ears, which is enough to render perceptual models, but it does not explicitly relate to direction. The 3DIR includes directional information and, therefore, relationships with the room geometry (the architecture of the space).

Two questions needs to be explored. *What are a necessary and sufficient number of:*

a) degrees of freedom?

b) data channels?

Only upon answering these can we discuss data compression. If we rely totally on perception-based models and the measurement of binaural room impulse responses, we may know how a room sounds, but may not be able to link the sound specifically to the architecture. We need to know both the perceptual and the spatial models in order to relate the sound field to the architecture and to perception.

Much of the recent work that has focused on the spatial aspects of sound fields is relevant to, indeed driven by, the analysis and design of auditoria. In this article we will review some aspects of spatial hearing, spatial measurements, modelling and auralisation. We will also look at what spatial sound fields are preferred for different events and how geometrical form can influence them.

Over the years, auditorium designs have responded to the growing understanding of spatial sound, but not enough. By understanding the links between architecture and acoustics, we are making greater progress in translating acoustical goals into room shapes. Through deep involvement with music and theatre performance, we understand which goals are appropriate for which rooms and which uses.

2. Perception

Our understanding of sound perception has come a long way since W.C. Sabine measured reverberation times by ear in Sanders Theatre [1]. An important leap came in the 1970s with the suggestions by Marshall [2] and Barron [3] and by the Göttingen [4] and Berlin groups that room width is critical to our sense of acoustical space. Their deduction that lateral energy has something to do with it has been accepted ever since. Just how much, and through what means, still remain the subject of debate. But we now do understand that all aspects of a room's shape – i.e. the locations, shapes and angles of its boundary surfaces – are audible.

Work by Jens Blauert [5] and others on spatial hearing has illuminated a great deal about the mechanisms and reasons behind our perception of space and timbre. Our ears, head and torso filter the sound before it gets to the auditory nerve, creating binaural dissimilarity that varies with frequency. The same mechanism creates a dependence of the perceived timbre (and loudness) of a sound, on its direction of arrival. An ensemble of reflected waves arriving from different directions is processed by the brain as an ensemble according to a complex set of rules.

Our sense of *envelopment* is due to amplitude and phase differences between the sounds reaching our two ears. Ando [6] and others have focused on the *Interaural Correlation Coefficient* (IACC) as a better indicator of the perception of envelopment. Griesinger [7] has related *Room Impression* to fluctuations in the amplitude and timing differences between the two ears.

Our perception of acoustical space seems to be multidimensional. Among the distinct perceptions of music in concert halls are what we currently call (a) *source broadening* and (b) *envelopment*. These have been linked to (a) lower frequency, earlier sound and (b) higher frequency, later sound, respectively. *Can we control them independently with architecture? Or with electronics? Do we want to?* It has been clear since the work of Keet [8] that some spatial effects are dependent on the overall sound level or, in effect, the absolute measure of lateral energy. There is little argument that these aspects of spaciousness (envelopment, etc.) are important in music acoustics, but there is little agreement on how much of them is enough. *Is there an optimum?* If so, it would seem to be dependent on the type of performance or repertoire of music which, in the end, is informed by the listeners' expectations and historical perspective.

In researching how we hear and what we like, we keep in mind the practical analysis and modelling applications. *What is sufficient accuracy?* If we try to model all the physics and hearing/psychological processes to the highest possible accuracy, we may be overdetermining the result if we cannot hear all the dimensions or all of the accuracy.

Abbreviations

3DIR	3D impulse response
BRIR	Binaural room impulse response
HRTF	Head-related transfer function
IACC	Interaural correlation coefficient
RT	Reverberation time

3. *Spatial sound measurement*

Sabine used his ears and a stopwatch to measure sound decays. Since then, the vast majority of acoustics measurements on auditoria have been, and still are, carried out with a single omnidirectional microphone. In the 60s and 70s we began to record and analyse impulse responses, looking at various energy ratios. These, for the most part, still involved single-channel data. Directional information was sometimes investigated with directional microphones and parabolic reflectors.

With the recognition that lateral sound and binaural dissimilarity are important in concert hall acoustics, Barron and others began to measure the *lateral fraction*, and Ando pushed forward with *Interaural Cross Correlation* and the *binaural room impulse response*. The lateral energy fraction at a point has been measured in halls for some years now, although Bradley [9], Beranek [10] and others have produced evidence that it is not well correlated with perception.

For concert hall and theatre designers, information on the spatial aspects of the sound field is helpful in relating the sound to the architecture in order to help us understand which surfaces ultimately reflect the sound to the listener. Moreover, we need to study the directional attributes of sound fields in halls and correlate them with perceptual attributes.

Our current goals for 3D measurements include the following:

- development of diagnostic tools to help understand the directional behaviour of the sound field in time;
- ability to assess the full 3D spatial impulse response, including pressure as a function of time and direction;
- ability to slice data across time and space;
- development of new approaches to visualisation, including animation;
- auralisation with measured impulse responses, independent of the specific ears used in recording;
- development of a library of 3D measurements made in many different facilities.

Large arrays for high directional resolution have been developed by several teams, including Elko (Bell Labs), Broadhurst, and Hanyu & Kimura. These can achieve high spatial resolution, but they are large and unwieldy, and depend on the precise alignment of many elements. However, we can recognize that four channels of information are sufficient in principle to describe fully the 3D spatial sound field, although at the expense of lower spatial resolution. The four channels are three *orthogonal directional vectors* and a *total pressure*.

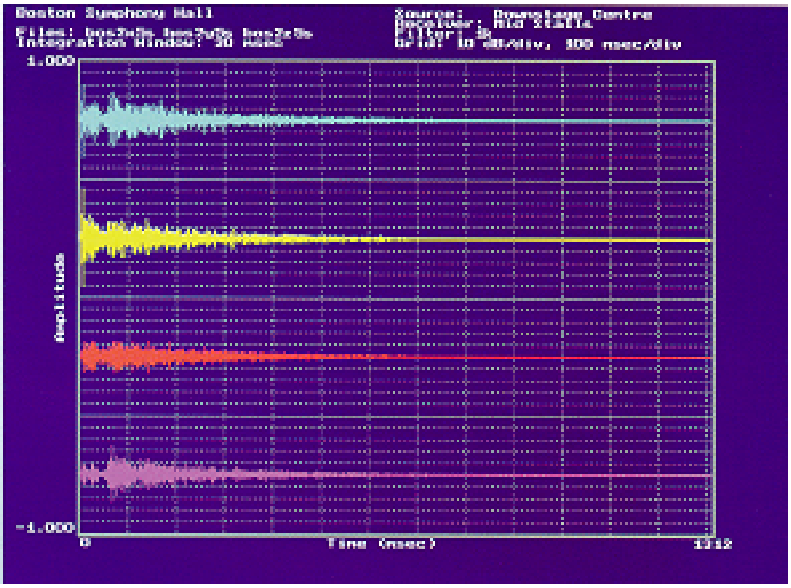

Figure 1
Four-channel B-format pressure output from a Soundfield microphone. Measurement of balloon burst impulse in Boston Symphony Hall (unoccupied), a tall, narrow, reverberant hall. Digitized to 16-bit resolution at 22050 Hz. The traces shown are the omni (W) , X, Y and Z components respectively with a vertical scale ranging from –1 to +1.

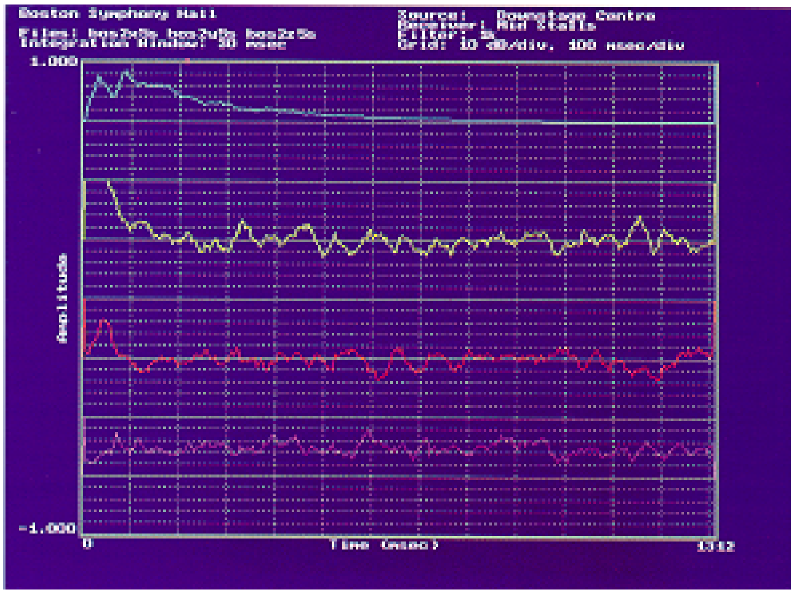

Figure 2
Smoothed directional fractions of the 4-channel response. The top trace is the smoothed omni (W) pressure response and the other traces are ratios of the dipole patterns to the omni channel, i.e. F_x, F_y and F_z respectively. This approach maintains the polarity of the pressure signal so that F_x is front-back, F_y is left-right and F_z is up-down. The vertical axis for each trace ranges from –1 to +1.

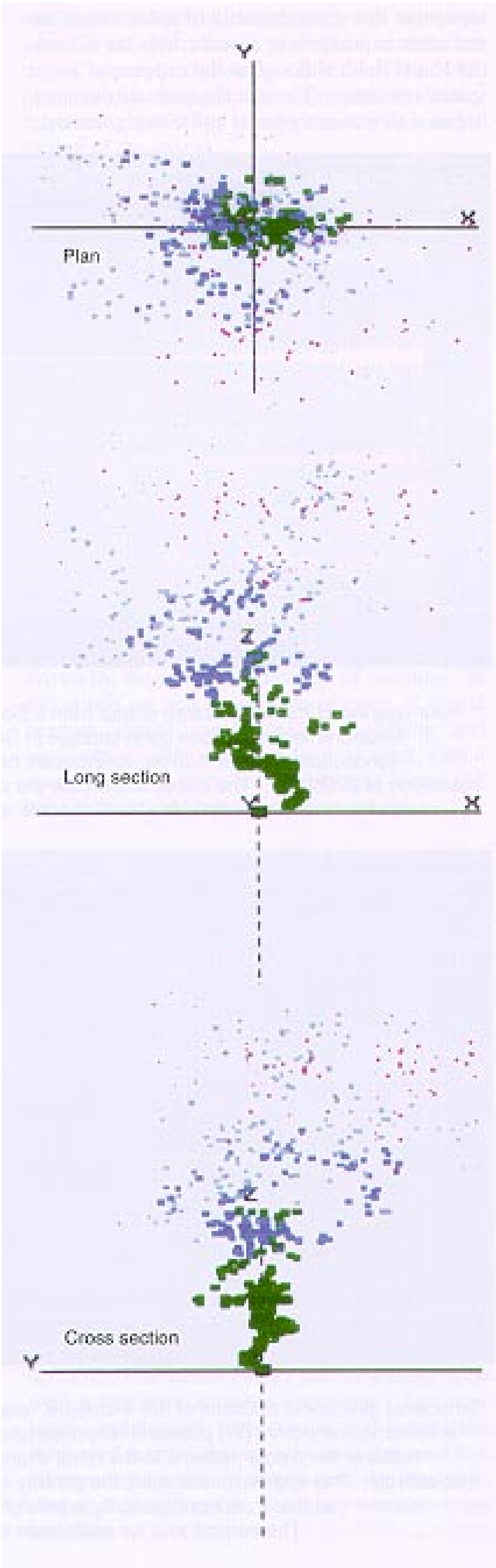

Figure 3
3DIR "cloud" plot derived from the directional fractions. Each of the 512 points in a fraction plot is mapped to a direction in 3D Cartesian coordinates, with the distance from the axis corresponding to time (total = 1300ms). Interpretation of the plot is enhanced by animation.

Several groups have developed room acoustics measurement systems based on four omnidirectional pressure microphones in a tetrahedral array:

– Yamasaki and Itow

– Sekiguchi, Kimura & Hanyu

– Korenaga

Another group – Abdou and Guy – has developed a 3D intensity method.

The Author has developed an approach, based on the Soundfield microphone, which was pioneered by Michael Gerzon [11] and Duane Cooper in the 70s. This device is a very closely-spaced tetrahedral array of four cardioid microphones, time aligned to measure the sound at a point at the centre of the array. The four signals are combined to give a pressure gradient (dipole, or "figure-of-8" directivity) response in the X, Y, Z directions and the omni-directional pressure response, W. This set of outputs has been called *B-format*.

The Author had been using an omni/dipole microphone pair for lateral energy fraction measurements and, along the way, has developed an approach to show the instantaneous lateral fraction. With the dipole microphone directed in the X, Y, Z directions, one could gather fractional energy in all six quadrants. Since the Soundfield microphone B-format outputs are equivalent to the cosine directivity pressure gradient microphone, we can use the same formula to derive the fractions for each direction X, Y, Z with the common W pressure response (*Fig. 1)*.

The process is a windowed product of the pressure and gradient channels, normalized by a sliding window average of the squared pressure channel, for a short time window (δ) that, ideally, would be chosen according to perceptual relevance.

The directional fractions for the X (front-back) direction are given by:

$$F_X(t) = \frac{\sum_{\tau=t-\frac{\delta}{2}}^{\tau=t+\frac{\delta}{2}} X(\tau)\, W(\tau)}{\sum_{\tau=t-\frac{\delta}{2}}^{\tau=t+\frac{\delta}{2}} W(\tau)\, W(\tau)}$$

where *W(τ)* is the pressure response
X(τ) is the pressure gradient (cosine directivity) response.

Smoothed directional fractions for the same data are shown in *Fig. 2*.

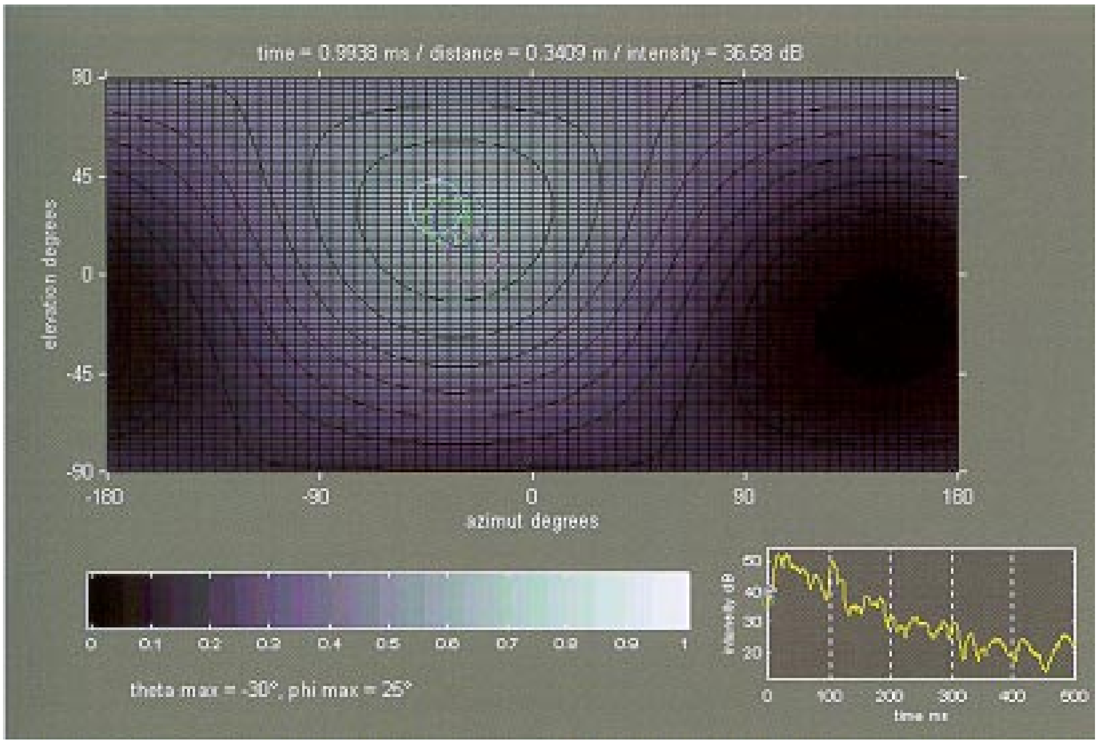

Figure 4
We can visualise the amplitude distribution with respect to direction and time on the inside of an expanding spherical shell by correlating the directional fractions with the directivity matrix of the soundfield mic on a frame-by-frame basis. This plot is a Mercator projection of one time frame of such a correlation, using a Matlab routine developed by Pierre-Antoine Grison. The circles show the scatter of different sub-values within the smoothing time window. (The data is from the 3D impulse response of a small theatre.)

The X, Y, Z fractions constitute the amplitude shading in each direction according to the cosine weighting of the microphone. We can therefore consider the three directional fractions to be "directional cosines" in order to establish the general resultant direction of sound at a particular instant with respect to the receiver (listener). Results can be displayed on a 3D axis in a "cloud" of energy that evolves over time (*Fig. 3*), or in a "Mercator" projection (*Fig. 4*).

4. Modelling and auralisation (sound rendering)

Acoustical modelling and auralisation techniques have helped us to understand spatial aspects of sound by visualising explicitly the 3D sound paths in the model and by listening to modelled phenomena. They have challenged us to think explicitly about some of the more detailed aspects of the behaviour of sound in halls, and of sound sources, as well as of perception.

Mainstream acoustical modelling in architectural projects is based fundamentally on geometrical acoustics, with ad hoc extensions for non-trivial phenomena such as edge diffraction, diffusion, and oblique angle absorption coefficients (*Fig. 5*).

Auralisation is the rendering of sound of modelled phenomena, a tremendously complex undertaking. Anechoic source sound is filtered through the synthetic (or measured) impulse response of the space and the appropriately modelled effects of the ears, head and shoulders (called the *head-related transfer function*, or HRTF). The resulting sound is played through headphones or a surround sound playback system such as Ambisonics. Auralisation allows us to listen to the phenomena we have heretofore judged on the basis of comparative numbers or graphics.

The directivity of instruments and voices has an influence on our perception of the timbre of the instruments and their loudness (and therefore their balance with others in the ensemble). Sound radiation from instruments is complex, the quality of sound being different in various directions. *How many directions are sufficient for modelling?* Loudspeaker manufacturers are now publishing the directivities of their horns at 10 degrees, but that may be overkill. Auralisation will help us to find what is the appropriate amount of detail.

5. Design evolution

The design of concert rooms has more-or-less followed the state of knowledge in concert hall acoustics. Certain basic shapes evolved for each performance/event type. This was not driven by a knowledge of any deterministic connection between room shape and sound, but rather (i) because of the way people gather naturally (for proximity and good sight-lines to the sound source), (ii) for structural capacity reasons and (iii) for social reasons.

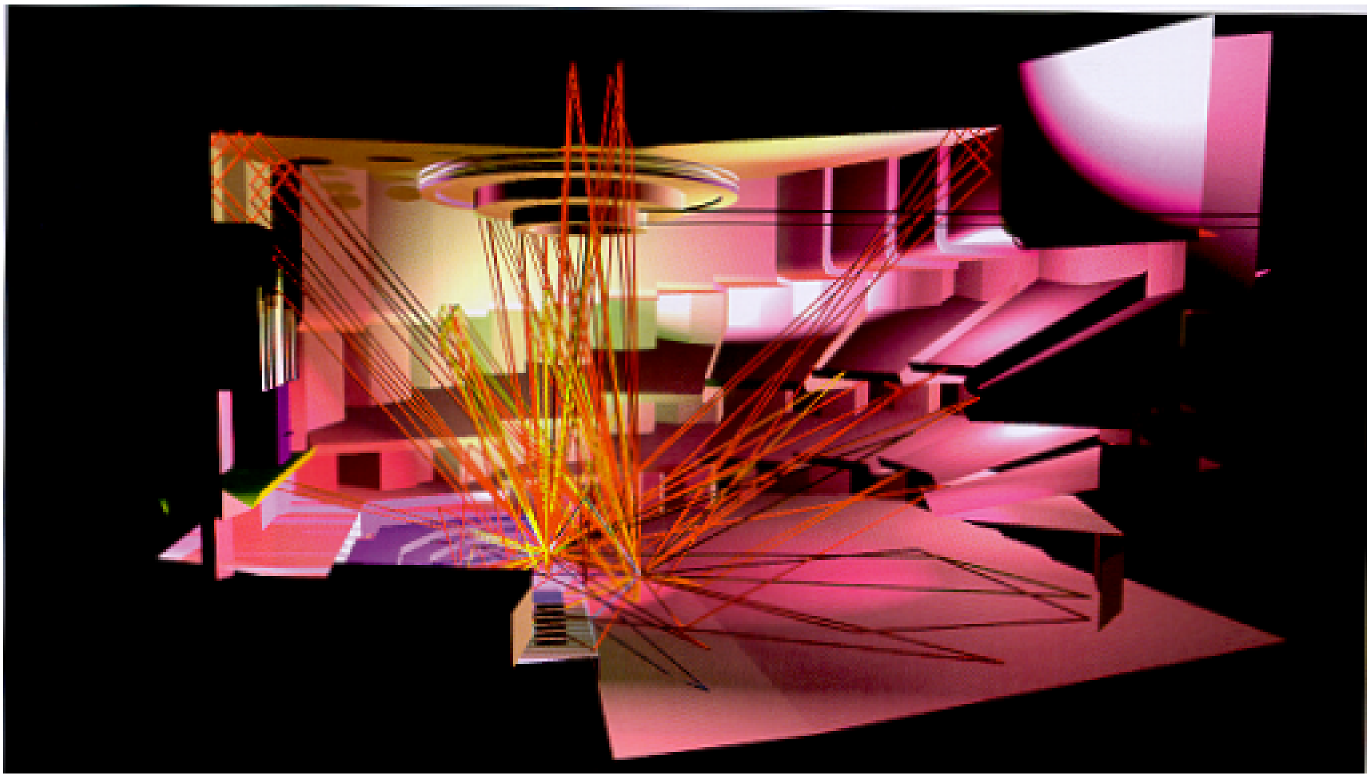

Figure 5
Computer model of a concert hall (near wall cut away), showing primary sound reflection paths between the source on stage and a listener in the front seating area. The ray colours correspond to reflections up to 3rd order which arrive between 0 and 80ms (cyan), 80 and 120ms (yellow) and 120 and 240ms (red) after the direct sound arrival.

At first, distance, clear sight-lines and shielding from noise were the principal factors considered. The plan shape and steep rake of open Greek and Roman amphitheatres brought people as close as possible to the performers, and the steep rake allowed the 1st-order floor reflection to benefit the listeners, and also served as a barrier from the street activity. Without a roof, this was essentially a 2-dimensional space with two parameters – *distance* and *seating slope*. Yet the Greeks and Romans also built roofed theatres that behaved as contained 3-dimensional spaces. Whether the ancients, including Vitruvius, knew the reasons for the acoustical differences between roofed and open spaces is an open question. *Did the higher level of loudness and reverberance under a roof influence the composition or performance of the odes and oratories of the day?*

Through much of the Middle Ages and the Renaissance, churches and cathedrals became more and more reverberant as buildings were designed taller. The sound absorption in these buildings is concentrated at the floor plane: the upper reaches are mostly vertical, hard, and rectilinear (except in the case of domes). The upper hard volume sustains the reverberation stronger and longer than in the lower portion near the audience. This is a so-called *loosely-coupled* volume system. In tall churches, one is familiar with the sense that the reverberance moves upwards with time.

Eighteenth and nineteenth century music rooms and concert halls were still limited in width by the clear span of timber trusses. Into the mid 19th century, the shaping was still mostly empirical, and the “shoebox” form was popular. Music of the time was composed with these performance rooms in mind, and these rooms provided a strong, laterally-biased reverberation.

Opera grew up in acoustically “drier” spaces, with the audience stacked along the side walls up to the ceiling. Still, a complete absence of reflections is not what was desired or designed. Beauty of tone and some sense of room sound is important for both the audience and the performers.

Chinese opera, typical of many Asian performing arts, evolved outdoors. Here there is no sense of indoor space, and not much in the way of reflecting surfaces. The piercing vocal techniques, the percussive orchestrations and the small audience sizes have been influenced accordingly.

5.1. The 20th century

At the turn of the century, Sabine found a simple relation between volume, area and sound decay time. We know this as the *reverberation time* (RT or T60), a one-dimensional parameter depending on volume and area.

After considering the volume and area, the next level of detail includes specific reflections. Certain 1st-order reflectors arrive at the listener from overhead. A low ceiling tends to promote low reverberance, lack of envelopment and a generally inadequate increase in loudness (as it directs sound into the absorbing audience).

In the early 60s, Leo Beranek postulated the importance of *Initial Time Delay Gap*, and this often led to arrays of small reflectors suspended below the ceiling. These allowed the ceiling to be higher, in order to sustain reverberance, but the reverberation was still addressed as:

– simply a function of volume and area, or the number of seats;

– the twin assumptions that (a) a diffuse field is perceptually desirable and (b) the late sound field, in large perceptually-*reverberant* halls, is diffuse.

Designs based on this approach resulted in several wide fan-shaped and oval halls with overhead reflectors. The halls of the early 1980s in Toronto (*Fig. 6*) and San Francisco were not received well. The analysis of what these halls are missing has led us to look at the importance of *running liveness* and the loudness of reverberation, and to take more seriously the notion that envelopment is related to the *loudness* of the lateral sound, both early and late lateral sound.

The importance of lateral reflections was advanced by Barron and Marshall. At first this spawned "first-order designs" where wall elements or applied wall panels were tilted downwards and inwards in order to direct strong 1st-order reflections to the centre of the audience. Examples include halls in Christchurch (*Fig. 7*) and Wellington (New Zealand) Nottingham (England), Colorado Springs (USA) and Glasgow (Scotland). One attribute of this sort of hall is a faster decay and greater clarity, because the tilted reflectors send the sound back into the audience. This fact has been used to advantage in multipurpose halls such as Colorado Springs and Basingstoke (England) among others. The development of reverberance in the auditorium is strong and lateral, but dies away fairly quickly, which is good for opera and musical theatre, where intelligibility is important.

In realizing that the reverberant *level* was important, we looked for ways to achieve strong lateralisation of the sound, and a strong reverberant level, or reverberation efficiency. The next step was to design for 1st- & 2nd-order lateral reflections. We can learn from the old rectangular halls that narrow, tall "shoebox" spaces provide 1st-order side-wall and ceiling reflections, and sustain the reverberance horizontally above the audience plane. This can result in a muddy sound if there is not enough early energy.

Adding a second and perhaps a third side-tier *soffit* returns more energy immediately to the lower levels. With appropriate dimensions, this geometry adds 2nd-order strong lateral reflections that promote clarity, envelopment and strength,

Figure 6
Roy Thomson Hall, Toronto (opened 1982, 2812 seats).
Plastic reflectors above the performance platform were incorporated to provide early reflections in order to make up for the great distance between most of the audience and the side walls. The sound has great (some say, too much) clarity but lacks envelopment, strength and bloom.

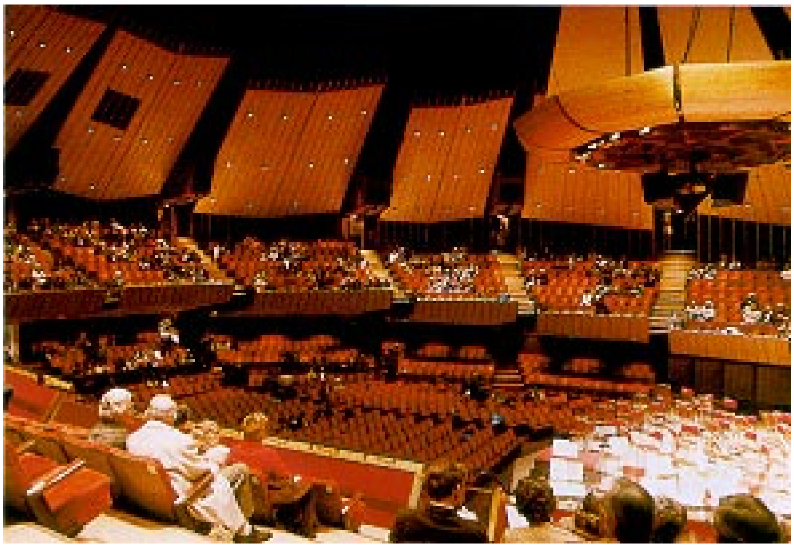

Figure 7
Christchurch Town Hall, New Zealand (opened 1972, 2662 seats).
Suspended reflecting surfaces at the sides are angled to provide lateral reflections to much of the audience. With so much sound directed initially into the audience, this hall does not sustain running liveness so well as one with vertical parallel walls.

Figure 8
Bridgewater Hall, Manchester (opened 1996, 2400 seats). A hybrid design with sparsely-populated side tiers whose soffits work with the side walls to serve as "2nd-order" lateral reflectors.

and it also retains the vertically-opposed surfaces that sustain reverberance. This is *reverberation efficiency*. A few older halls, such as Carnegie Hall (New York), have the audience densely stacked at the rear, and sparsely arranged on the side tiers. This supports lateral energy and not much extended front-back energy flow. In halls where there are few people on either the side or rear walls at high level, reverberance is developed between the side walls and between the front and rear walls, but there is a different time constant, or group delay, between the two. This has been applied to excellent effect in the design of contemporary "rectangular hybrid" halls in Birmingham and Manchester (*Fig. 8*).

5.2. Variable absorption

Listeners want to feel surrounded by reverberance in the case of symphony, organ, and choral concerts, in balance with an appropriate measure of directional fidelity. In amplified events, the clarity, intelligibility and directional fidelity are considered more important.

Variable sound absorption systems affect the spatial qualities as well as the time response. Spatial definition can be controlled by varying the lateral energy. When the absorbing system covers the lateral reflection surfaces, the apparent source width and envelopment are reduced, and the loudness and clarity are reduced more than if the ceiling were covered.

Likewise, reverberance can be controlled most efficiently by covering the surfaces that are most responsible for sustaining the reverberance: in the case of a shoebox hall, the upper side walls

5.3. Variable volume coupling

Coupled volumes have been used to provide extended reverberance. In multipurpose halls, coupled spaces have been developed with variable success from "found space" such as stage fly space. In concert halls, coupled volumes have surrounded the top of the room (*Fig. 9*). New designs will bring the chamber down lower around the performers and audience.

This leads to a consideration of variable dimensions. Movable ceilings have been incorporated in quite a few facilities in order to provide variable height. Often the resulting variation in volume drove the design criteria. Variable width is also being considered.

5.4. Electronic spatial control

The developments outlined in *Section 5* are leading towards an ability to tailor the acoustical spaciousness of a room, much as we have been tailoring the decay rate. Just as our control of time response has moved from a period of architectural

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From 1997 to the present time, Bob Essert has been with Arup Acoustics in London where his current projects include a new concert hall in Gateshead, UK, a new lyric theatre in Cardiff, Wales, and renovations to the Hackney Empire Theatre, London. Under his guidance, Arup Acoustics is developing a 3D auralisation studio to complement the group's acoustics consulting work.

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development into electronic solutions, so our control of spatial aspects is moving through a stage of mechanical/architectural control systems into electronic mimicry of the architectural solutions. Electronic control is beginning to address areas that are not, or cannot be, dealt with architecturally, such as:

- surround sound effects;
- surround sound cinema;
- home theatre;
- virtual environments;
- variable spaciousness;
- real-time direct performer control (e.g. MIT Medialab's “Hyperinstruments”).

6. Conclusions

In this article we have reviewed some aspects of spatial hearing, spatial measurements, modelling and auralisation. We have also looked at how auditorium designs have responded to the growing understanding of spatial sound. Increased understanding of the links between architecture and acoustics is allowing greater progress in translating acoustical goals into room shapes. As hall designers we have become more proactive, with the acoustical characteristics of room-shaping playing a more important role in the overall design.

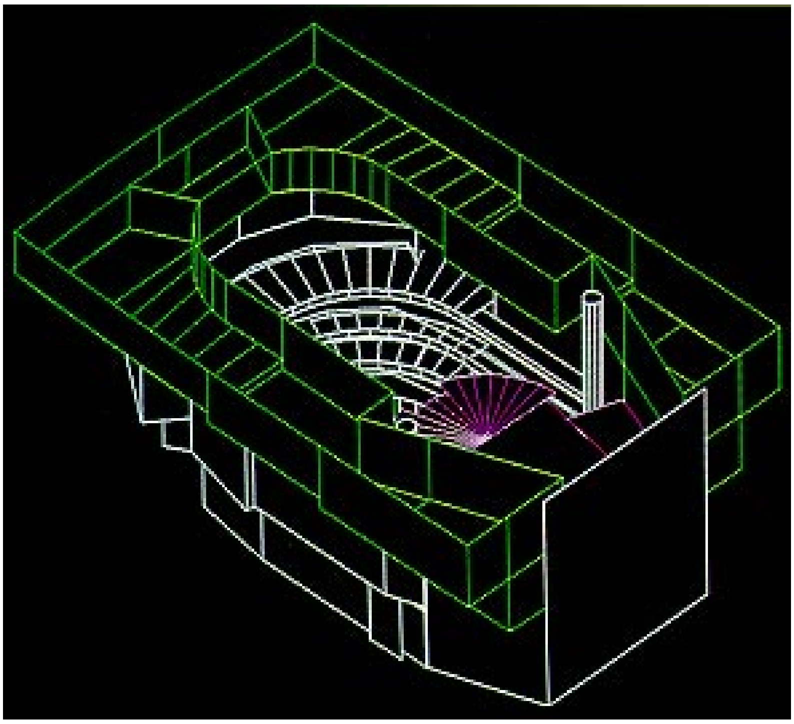

Figure 9
Top-view diagram of Meyerson Symphony Center in Dallas (opened 1989, 2065 seats). A partially-covered reverberation chamber (shown in green) wraps around the upper part of the hall. The flow of sound energy between the audience chamber and the outer chamber is controlled with a set of large concrete doors. This approach has provided variability of, and independence between, the clarity and reverberance. A similar approach was used in the Symphony Hall, Birmingham.

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