

# The New Understanding of Acoustics

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The twentieth century is littered with concert halls that have failed to meet their owners' expectations. Brutalism, an unfortunate architectural moniker, might easily be applied to the acoustics of several post-war performing arts venues. Recently however the tide seems to have turned. In the last ten years, halls in Taipei, Hong Kong, Dallas, Glyndebourne and Vancouver, to name but a few, have opened to critical acclaim. So, what is behind this new found success? To answer this question, we need to place the post war theatre building boom into historical perspective.

At the turn of this century, a reluctant scientist named Wallace Clement Sabine accepted a commission to provide acoustical advice for the new Symphony Hall in Boston. It would become the first concert hall to apply deductive scientific reasoning in its acoustical design. Panned by some when it first opened, it now stands as an acoustical landmark, one of the world's favourites.



There are many lessons to be learned from Sabine's pioneering work on Symphony Hall. Most readers will be familiar with his definition of reverberation and the formula he developed to predict it. This became the foundation of a new independent branch of science - **room acoustics**. In hindsight, however, we know that most of the success of Symphony Hall can be attributed to its classic shoe box shaped format. Contemporary science played a role in achieving success but perhaps not a leading one. At Symphony Hall, science worked hand in hand with craft rather than one dominating the other. It would take seventy years of acoustic research to unlock the secret of the shoebox. Working without the benefit of this

knowledge, Sabine was able to design a highly successful room through judicious reference to its two antecedents, the old Leipzig Gewandhaus and Boston's Music Hall.

By the 1950s a number of halls had been designed using Sabine's reverberation formula and many, if not most, were failures. At the time, reverberation was thought of as the paramount concern in acoustical design. Indeed, before the age of computers, it was one of the few things that acousticians could predict with any confidence. We now know that acoustics is a multidimensional experience. Clarity, Spatial Impression, Reverberation and Loudness are probably the four most important parameters although, depending on the situation, there may be more. Thus acousticians of today are concerned with: the timing of the first few reflections (for Clarity); the direction at which both early and late reflections arrive at the listener (Spatial Impression); the overall strength of the reflected sound (Loudness); and how fast the sound decays (Reverberation).

None of this was known when the post war theatre boom started. For acousticians like myself, rooms like London's Royal Festival Hall (1951), The Queen Elizabeth Theatre (1959) in Vancouver and Berliner Philharmonie (1963) are monuments to the people who worked on them. For the people who had to use them however, only the latter was ever held in favour. Other room's, like Toronto's O'Keefe Centre (1960) were, until very recently, openly despised.

Fortunately, as one acoustical failure followed another, university based research was initiating a revolution in our understanding of the propagation and perception of sound in the built environment. The results were to have a profound effect on auditoria design and, in particular, the shape of auditoria.

## CLARITY

It was discovered that our hearing, much like our other senses, has a "flicker rate". We've all seen a motion picture speed up from a standing start. Our hearing acts the same way. If reflected sound is heard soon enough after the sound coming directly from the stage, the ear will integrate the reflection as a useful or supporting component. If the reflection is too late, it will interfere with the direct sound, just like a movie that isn't moving fast enough.

The "flicker rate" of hearing is about 1/20 of a second or less. This means that the early reflections in a room are very important, implying that the room shape is also important. This has led to the overhead reflectors present in almost all new theatres. It also explains why large rooms are harder to design than small rooms. In a small room the reflecting surfaces are close to all the listeners which ensures short reflection paths and appropriately "early" reflections. The challenge in a larger room is to get as many listeners close to the reflecting surfaces as possible. One of the more elegant solutions to this problem is found in the layered audience levels of Hans Scharoun's Berliner Philharmonie.

## SPATIAL IMPRESSION

Perhaps the most important discovery about our perception of sound in rooms was the realization that sound from the sides is beneficial. Studies carried out at Southampton University in the late '60s and early '70s found that sound arriving at the listener from the side will promote a feeling of acoustic envelopment. The manager of Amsterdam's Concertgebouw described it as

*"...the difference between being immersed in the sound and looking at it, as through a window."*

This is a characteristic displayed by all of the world's favourite halls and is truly a wonderful experience. Shoebox shaped rooms such as Vienna's Musikvereinsaal and the old Leipzig Gewandhaus, and yes, Sabine's Boston Symphony Hall are narrow and provide lots of sound energy from the side walls.



The effect of the lateral reflections thesis on concert hall design can be seen in the re-emergence of the shoebox configuration. Post-modernist's are, of course, eager to implement classic formats and must take some of the credit for this acoustical renaissance. It's worth noting however that Scharoun's thoroughly modern Philharmonie also satisfies the lateral energy thesis. In this it can be seen as prescient. The first published references to the benefits of early lateral energy date from 1966. Berlin Philharmonie opened in 1963.

## LOUDNESS

Although Sabine had written of the importance of Loudness at the beginning of the century, few considered it of any significance until the 1970s. Three independent surveys of German and British halls all pointed to the importance of Loudness. This came as a surprise to many. The difference in Loudness from one hall to the next is not often large. Smaller, in fact, than what might be considered subjectively significant in another setting, for example a factory or office. The listening experience in a performance venue however is more acute. Around the office we might be sensitive to a change of 5 to 10 dB. In a concert hall differences as small as 1 or 2 dB are important, both for expert and casual listeners. The Loudness of a room depends on its size. Small rooms are loud and large rooms (e.g. over 1,800 seats) are often not loud enough.

To summarise, we now know at least three things that postwar designers didn't. Listeners need to be close to large reflecting surfaces to ensure musical Clarity. To achieve a Spatial Impression of the room, the reflected sound should arrive at the listener from the sides. Loudness is also an important issue. In many cases, the easiest way to achieve adequate Loudness is to limit the size of the room. And of course there is Reverberance, the one thing the postwar modernists did know about ... or did they?

## REVERBERANCE

It turns out that the Sabine's definition of Reverberation Time was not entirely appropriate for music. The reason for this can be quite easily explained. The ideal Reverberation Time for a concert hall is about 2.0 seconds. By Sabine's definition, that's the time it takes sound to decay 60 dB - that is from a loud sound to inaudibility. Now, imagine a performance in where each musical note is separated by 2.0 seconds. The evening would go on forever! In most musical passages, the notes are separated by small fractions of seconds. The only time one might hear the entire 2.0 second reverberation in a concert hall is at the end of a piece of music. In the 1960s it was found the early part of the decay, those first few fractions of a second, correlates much better with the subjective assessment of reverberation than Sabine's 60 dB definition.

If there is a new confidence in room acoustics design, the turning point would probably be found in Christchurch, New Zealand, circa 1972. Its 2650 seat arena shaped Town Hall was the first room to be designed using the "sound from the sides" theory. Large overhead reflectors along the side walls of the room provide the required amount of early lateral sound for good source broadening. The room has at least 500 seats more than previously thought practical, layed out in a difficult elliptical plan. Despite this and its remote location, it is renowned for its good acoustics. After Christchurch, most of the rooms designed to promote good lateral reflections have met with success. One of the first in North America was Kitchener's Centre in the Square.



As important as lateral energy is however, it will not on its own guarantee good acoustics.

There are no acoustical panacea. Remember, the perception of sound is a multi-dimensional experience. The rooms in Christchurch and Kitchener have good Spatial Impression as designed but they also have the appropriate Loudness, Reverberance and Clarity. One of the few "lateral reflection" rooms that hasn't worked was designed to emphasize lateral energy but did not provide enough reverberance. In a survey of British auditoria acoustics it was rated as good but not great.

## CASE STUDIES

With the recent resurgence of modernism – some call it neo-modernism – I thought it might be interesting to apply all this new found acoustical knowledge to Canadian modernism's two big theatres: Peter Dickinson's O'Keefe Centre in Toronto and Fred Lebensold's Queen Elizabeth Theatre in Vancouver. O'Keefe Centre (recently re-named the Hummingbird Centre) is visually the more elegant of the two but, unfortunately, was Dickinson's only major theatre. He died not long after it opened, just short of his 36th birthday. The Queen Elizabeth Theatre was the first of many theatres for Lebensold and the team that became ARCOP. It's influence on post-war theatre design cannot be over-stated. His team and its progeny have designed – and continue to design – performing arts centres throughout North America. Two complete issues of Canadian Architect were dedicated to the building. One for the design competition (May 1956) and the other when it opened (January 1960).

Both of these rooms are noted for their poor acoustics, although perhaps Toronto's building more than Vancouver's. But the Queen Elizabeth model improved as the years rolled on and it spread east across the country. It is said that during his many successful presentations to building committees in the 1960s, Fred Lebensold would spend the first ten minutes on the topic of the Queen Elizabeth Theatre. Just when people were starting to fidget he would deliver the punch line "... and we never make the same mistake twice!"

The Hummingbird Centre is fan shaped in plan, which explains in part why it was acoustically inferior to its Vancouver cousin. Both rooms are wide and flat. This is in contrast to the traditional shoebox shaped room, which is high and narrow. (We later found this fact to be quite important.) Both have a single balcony but in the Queen Elizabeth Theatre the balcony extends along the side walls in a "ski slope" of seating. The side walls of the Hummingbird Centre were a flat pattern of cherry wood panels forming a graceful curve into the proscenium arch located at the fulcrum of the fan.

During recent renovation work, I have had the opportunity to perform acoustical measurements in both rooms. Measurements with the hindsight of everything we have discussed so far. To the credit of both design teams, the Reverberation Time in both rooms is exactly where it should be. In other words, they delivered the thing that they thought was important – the only thing the embryonic world of acoustics knew about. Unfortunately, everything else that we now know as being important is miles of the mark. Although they got the Reverberation Times right, neither room can be considered reverberant in subjective terms. Measurements of the first part of the reverberant decay explain why. The so-called Early Decay Times vary significantly, in some cases almost beyond belief. One seat in the old O'Keefe Centre had an Early Decay Time of 0.24 seconds. This is worse than an office or living room.

As one might expect from rooms that are not reverberant enough, measured Clarity is high, probably too high. Both rooms are wide, which implies poor lateral reflections. Consequently, neither room is known for good spatial impression, let alone the envelopment of sound that the manager of the Concertgebouw described so well. Again, the measurements confirm this. Perhaps the most serious problem in both rooms is Loudness. Comparisons between the Queen Elizabeth Theatre and 12 other North American halls demonstrate the extent of the problem. In the Queen Elizabeth Theatre an orchestra would have to double its size just to match the Loudness in the worst of the other 12 halls. At the Hummingbird Centre, the situation was even worse. Loudness levels were so low that, for all intents and purposes, the room was devoid of reflected sound. Nothing could be more fundamental. Reflections are what room acoustics is all about. In a field of grass there are no reflections, in a room there are. It's as simple as that.

So what does one do with these rooms, or a room like them? Fortunately, there are now two reliable options: natural acoustics and electro-acoustics. At the Hummingbird Centre, both technologies had to be applied and architectural changes were kept to minimum. At the Queen Elizabeth, the proposed renovation may rely completely on natural acoustics. In this case, a second balcony will be added and the ski slope of seating along the side wall will be replaced with three tiers of boxes. The ceiling will also be modified. As might be expected, neither of these renovation designs was a smooth process.

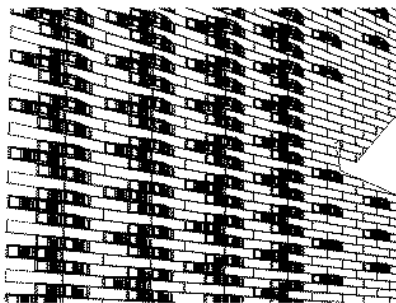
## HUMMINGBIRD CENTRE

The Hummingbird Centre seemed to be the perfect candidate for electro-acoustic enhancement. These systems, although very powerful, do have their limitations. Their main purpose is to add Reverberation to a room. But this can't be done without increasing Loudness. In a small room (which by nature is loud) this becomes a problem. One quickly reaches a point where either the new system sounds unnatural because it's too loud or it can't be heard over the room's natural acoustics. At the Hummingbird Centre with its barely audible natural acoustics, an enhancement system seemed to be a perfect fit. That was until the side wall echoes were discovered.



These echoes had been there since the room opened in 1960 but had never been a problem. That was because the curved side walls in the fan shape plan were never fully exposed to sound coming from the stage. The enhancement system design called for loudspeakers all over the side walls, each one of them directing sound at the opposite (focussing) side wall. An aberration that had laid dormant for almost forty years threatened to derail the entire project. The design challenge was formidable. How does one introduce bumpy acoustical diffusers onto Dickinson's elegant, flat walls and make them look like they belong there?

The design solution can be seen below. It shows our original design incorporating loudspeakers for the system and stepped acoustical diffusers to reduce the echo. The proposal was submitted (with some trepidation) to architect Tom Payne for his review and input. Tom saw the solution immediately. His idea was to create a "basket weave" of acoustical diffusers and, to that end, he encouraged us to smooth out the profile.



The stepped diffuser in the original design is essentially a contiguous series of wells of varying depth. The width and depth of the wells are determined using relatively simple calculations and a little bit of prime number theory. This type of diffuser has been widely used since it was introduced in 1978 as the first deterministic form of diffusion. The process has recently taken a giant step forward through the use of computer optimisation. Instead of determining well width and depth with simple prime number calculations, the computer is used to iteratively optimise the well

dimensions. For the Hummingbird, the result was a crescent shape which, quite coincidentally, fit perfectly with Payne's concept of the basket weave. (The optimisation routine for the Hummingbird diffusers was run by its developer Trevor Cox at Salford University in the UK. At the time he was unaware of Tom Payne's suggestions.)

With the diffusers in place most of the echo has been removed. This then allowed us to turn up the enhancement system without fear of echo or acoustic image shift. The new acoustics appear natural, without a trace of the artificial "tinny" sound that has plagued this type of electronic solution in the past. Dickinson's room has a new lease on life – at least in terms of acoustics.

## QUEEN ELIZABETH THEATRE

Renovation work at the Queen Elizabeth Theatre is no less intriguing. Like the Hummingbird Centre, the bulk of this design is being tested with a physical scale model rather than a computer model. It's tempting to respond to the new design on an intuitive level. With the side boxes and double balcony, it just looks like it should sound better! In truth, the first attempt at the side boxes actually made it worse.

The new design was prepared by Thom Weeks of proscenium architects and was tested at their offices in Vancouver. Testing started with a model of the original building then became an iterative process as the parts for the new design were built and installed. Changes to the front and back of the ceiling improved the Reverberance. Then we added the second balcony, which improved both Loudness and Reverberance. But when the boxes were added, all the Reverberance we had gained quickly evaporated. Tests were repeated three times, each one confirming the first results.

From this, and with really nowhere else to go, we initiated a controlled computer study in the hope that we could find out exactly what was going on. On a suggestion from a colleague at the University of British Columbia, we studied the effect of the height to width ratio on the Reverberance. Sure enough, we found that (under controlled conditions) wide rooms with low ceilings, like the Queen Elizabeth, have poor reverberance while tall narrow buildings, like a shoebox, have good reverberance. This was the root of the problem. If we could make the room narrower, we could regain some of the reverberance we had lost to the boxes. Doing this would also improve lateral reflections and thus improve Spatial Impression.



A second computer study suggested that deep boxes, like the ones we were using, also reduce Reverberation. Just as I was about to send this last result off to Thom Weeks, he sent me a drawing with large side wall reflectors that effectively reduced the depth of the boxes by more than half. In other words: before I could explain the problem, he had the solution! (This in my experience is not all that rare. In a good interdisciplinary effort the solution seems to germinate for a while and can then pop up anywhere.)

A new version of the model was prepared and tested. Results at press time are preliminary but it seems clear that we now have the proper Reverberance and Spatial Impression.

## ENIGMA

We have learned quite a bit about acoustics in the last forty years. The puzzle is by no means complete however. A recent French study found that a group of listeners used at least 13 different attributes to judge the sound in a room. The multi-dimensional nature of acoustic judgement is a fascinating enigma, at once alluring and confusing. Although we only need three dimensions to build a theatre or concert hall, it appears we need no less than 13 to make up our minds about its acoustics! That's the bad news. The good news is that there is general agreement on the four most important attributes: Reverberance, Loudness, Clarity and Spatial Impression.

... but not necessarily in that order!