

“The Early History of Ray Tracing in Room Acoustics”

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THE EARLY HISTORY OF RAY TRACING IN ROOM ACOUSTICS

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Introduction

In 1968, the paper titled “Calculating acoustical room response by use of a ray tracing technique” was published by Asbjørn Krokstad, Svein Strøm, and Svein Sørsdal [1]. It was published in the relatively recent *Journal of Sound and Vibration* and the paper has been a remarkably relevant paper throughout the almost 40 years that have passed since its publishing. It was the first paper that presented the computerized ray tracing technique for finding the impulse response in any three-dimensional model of a room. The reason that it has stayed relevant is that computerized prediction techniques continue to be an active research area. Also, computerized prediction of room acoustical responses still rely on the ray tracing technique to a large extent. As an example, the two leading commercial softwares that are used by practitioners today, CATT Acoustic [2] and Odeon [3], both use variants of the ray tracing technique. Furthermore, a look in the journal paper citation database *ISI Web of Science*SM reveals that this paper was cited four times in 2006, eight times in 2007 and has already been cited twice in 2008. altogether, 60 times. These are high numbers for a decades-old paper in a field which is a relatively small research field.

In this paper, I will try to present some of the work in Trondheim and other places that lead up to the publishing of this paper. It is a view from the outside, and by someone who wasn't there when it happened. Two other views – by Asbjørn Krokstad and by Svein Strøm – that are presented in other papers in this book offer the opposite: a view from the inside, and from the time that it actually happened.

First studies – mean free path calculations

In the 60s, researchers started to use computers for solving demanding numerical problems. The computers offered a new and more efficient tool to solve an existing problem, or to get better, more accurate results with the same algorithm that had been used before. The computers merely sped up the calculations compared to before. Within acoustics, some of these fundamental questions lead up towards the general ray tracing method.

The field of room acoustics gives an interesting example of how the computers offered a straightforward improvement to numerical studies. Sabine's famous equation from 1898 claims that the sound level in a room decays linearly with time, that is, an exponential decay for the sound pressure amplitude. The decay rate was determined by a very simple relationship,

$$T_{60} = 0.163 \left[\text{sm}^{-1} \right] \frac{V}{\alpha S}$$

where V is the room volume, α is the average absorption coefficient and S is the total surface area of the room. Researchers have been kept busy by studying if this simple formula is true in any room geometry. The simple diffuse-field analysis involved the so-called mean free path length in a room, that is, the average length that a sound wave can travel between wall hits. This mean free path length had been established theoretically for some simple room shapes but novel approaches were used to find the mean free path in rooms of other shapes. In his classical book from 1932, *Architectural Acoustics*, Vern Knudsen described experiments where he used light rays in a scale model to figure out where sound waves would hit during several consecutive reflections [4]. By marking hit points on walls and measuring the corresponding lengths, he could collect data on these path lengths. Obviously, the accuracy was quite limited but he did find that quite different room shapes seemed to give the same average path length, or "mean free path". Such optical techniques in scale models continued to be in use, but also drawings offered similar possibilities.

A first step towards computerized ray tracing was to collect data on the path lengths and the collision probabilities of the walls using a computerized Monte Carlo technique, by Allred and Newhouse in 1958 [5]. They studied rectangular/shoe-box shaped rooms and Fig. 1 illustrates that the algorithm was quite straightforward. The algorithm generated rays in a number of randomized directions from one source position. For each ray, its path was followed via a succession of specular reflections. Data on path lengths and which reflection planes that were hit, was stored. Allred and Newhouse did not specify which computer they used, or calculation times but they could follow 10 consecutive reflections for each ray, and they used 150 rays that were emitted in random directions.

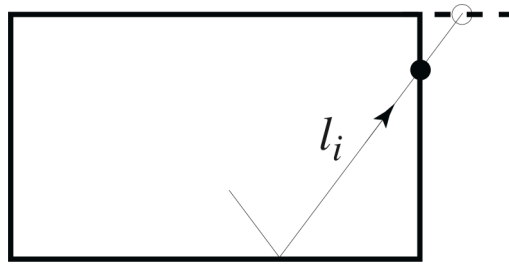


Figure 1 Illustration of the Allred and Newhouse algorithm from 1958. Their paper studied three dimensional shoebox shaped rooms; here a two-dimensional version is drawn. Each ray was reflected specularly and the next hit point was chosen as the closest of the three (two for the two-dimensional version) possible crosspoints with other planes. The data sought were the lengths of the free paths, l_i .

This computerized calculation method gave accurate values for the mean free path in various shoe-box room shapes and showed that there will be different reverberation times in various room shapes. Two follow-up papers pointed out two errors in the original paper: the authors themselves found a programming error that gave around 10% too long rev. times in the first paper [6]. Then Hunt, in 1964, showed that they used a randomization of the source emission directions which did not correspond to an isotropic sampling of the sound field [7].

In this first implementation of ray tracing in room acoustics there were a number of developments that they did not have to worry about. Some of these necessary developments were more or less a degree of refinement of the original algorithm:

I. How to handle non-shoebox shaped, but convex, rooms, see Fig. 2(a). The equations for finding the crosspoint between a line and any plane were well known, of course. So, conceptually, no major step needed to be taken since the same algorithm step can be used: compute the next crosspoints between a ray and a number of possible wall planes. The closest following wall hit point must then be the next valid reflection point.

II. How to check for obstructions, such as finite reflectors, and convex room shapes, see Fig. 2(b) and (c). This step requires the computationally somewhat more demanding task of checking whether the next, closest reflection point "candidate" is within a finite plane or not.¹

¹ The difference between convex and non-convex room shapes is rather important from an efficiency point of view. Today's most efficient methods for geometrical acoustics often subdivide a complicated room volume into convex sub-volumes for a much more efficient processing [8].

III. How to handle specularly and diffusely reflecting surfaces. This was also relatively straightforward to handle but every ray could not be split up into specular and diffuse components since that leads to a computation time “explosion”. An important simplification was to use a stochastic approach and let each reflected ray become either specularly reflecting or diffusely reflecting. In the long run, when averaging over many rays and/or many repetition runs, the final outcome will be correct.

IV. How to "collect" the result in the form of an echogram, or energy impulse response, for a specific receiver. This was the important step to take in order to study receiver-specific responses.

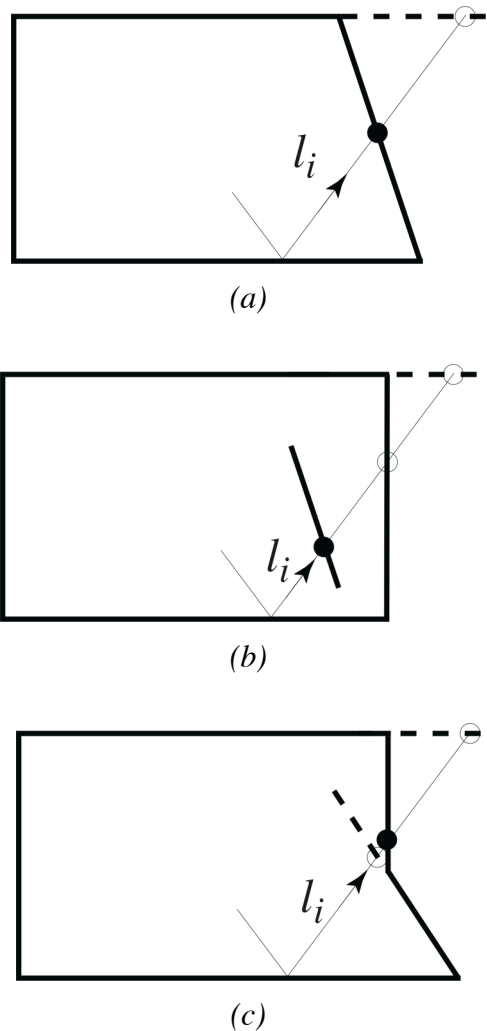


Figure 2 Extensions from the shoe-box room. (a) Non-shoebox shaped, but convex room shapes. (b) Non-convex room shape (i.e., with obstructions) (c) Room with free obstructing objects.

Allred and Newhouse did outline an extension of their work:

“The Monte Carlo method of machine computation is shown to be applicable to the evaluation of room acoustics. Its extension to the study of reverberation time is straightforward, and air absorption, as well as frequency dependence of air and absorbers, can also easily be taken into account. It would be a simple matter also to vary the absorption coefficient as a function of position, either discretely or continuously, ...

The method is also applicable to the study of coupled rooms and rooms of irregular shape, such as auditoria. The complications are geometrical, and are of degree rather than kind as referred to our parallelepiped calculations.”

Apparently, they did not follow this path of development. It could be noted, however, that the reverberation time was their focus also for future directions of the research.

The path towards auralization

A visionary conference paper by Schroeder et al at the ICA in Copenhagen in 1962 was titled "Digital computers in room acoustics" [9]. That paper was remarkable in that it laid out the methodology for what much later was to be called auralization, that is, to be able to listen to computerized simulations of the sound in a room [10]. The auralization process was still in the early 1990s a computationally very demanding process but Schroeder had identified the necessary steps:

The use of computerized convolution between a (simplified) impulse response and anechoic music.

The cross-talk cancellation technique for the presentation of binaural sound over two loudspeakers in an anechoic room, which can give the impression of sound incidence from any direction.

The development of a natural sounding reverberation unit without needing to carry out a convolution with a huge number of discrete reflections.

Interestingly, Schroeder mentioned that discrete echoes can be handled by discrete delay units but otherwise said nothing about the computation of the detailed impulse response. Rather more focus was given to the use of computers for implementing Schroeders earlier (1954) seminal work on the statistics of frequency response functions [11].

Computing decays in generally shaped convex rooms

After the Allred and Newhouse study, and some subsequent theoretical discussion papers on mean free paths, other studies were looking into the computation of reverberation time (rather than mean free path and collision frequencies). In order to compute the decay, point III (and in principle also IV) above needed to be introduced. At each reflection, the ray's energy was decreased by the wall reflection factor. Then, each ray gave a little contribution, at the time given by the total propagation path length, which was determined by the ray's reflection history. This extension was presented by Atal and Schroeder at an ASA meeting paper in April 1967 [12]. ASA meetings don't publish any papers, so all that is available is an abstract, plus some example results in two later papers by Schroeder in 1969 and 1970 [13, 14]. It did seem like Atal and Schroeder did have a functioning program for points I and III above, however, only for two dimensions².

The Atal and Schroeder algorithm was presented in the JASA paper in 1970 and results were given that showed that the reverberation time could vary widely depending on where absorbing surfaces were placed [14]. The paper did not cite the 1968 Krokstad, Strøm and Sørdsdal paper, which was probably a consequence of that JSV was a recent and European journal. As indicated above, the 1970 paper by Schroeder did not present algorithms for handling convex room shapes or reflectors. Also, the calculation of individual receiver positions was not discussed - their algorithm computed a global decay history since the decay was recorded every time a ray hit any wall, that is, no receiver-specific responses were calculated.

Diffuseness of reverberation rooms with hanging reflectors

Wilhelm Løchstøer was associate professor at the University of Oslo, Department of Physics,. He specialized on acoustics and was one of the founders of the Acoustical Society of Norway in 1955. In the early 1960s he supervised Asbjørn Krokstad for his PhD work on room acoustics (see also [16]). This triggered an interest in computerized studies of sound transmission for Løchstøer and one of his students, Nikolai Stenseng, wrote his Master thesis on “The influence of diffusers on sound absorption measurements of a small volume” in January 1965 [17]. This thesis by Stenseng was quite a significant

² In a paper by Wayman & Vanyo in 1977, [15], the quite trivial extension of Schroeder's approach from two to three dimensions was presented, with no reference to the 1968 paper by Krokstad et al.

development from the previous studies at that time, [5-6], in that it implemented a ray tracing technique for a 3D room, albeit shoe-box shaped, but with free-hanging diffusors. These diffusors were always parallel to one of the walls, which made the computation of obstruction checks somewhat easier. Since reverberation rooms typically have smooth and flat walls and reflectors, only specular reflections were implemented and the need for something else was not discussed either. The program was written in the language Fortran IV for the computer UNIVAC 1107 (which had been delivered to the Norwegian Computing Center in August 1963).

An extension of this study by Stenseng was the master thesis by Svein Strøm in 1967, on “The diffusivity in small reverberation rooms with and without diffusors”, also under Løchstøer in Oslo [18], [19]. Strøm expanded Stensengs study by implementing oblique reflectors, and also spherical reflectors. Furthermore, Strøm also computed actual decay curves, rather than collecting statistics data on path lengths. The purpose was still, however, to study the reverberation time.

Putting it all together into a computerized room acoustic design tool

The 1968 paper by Krokstad, Strøm and Sørdsal, [1], was aiming not only at finding the reverberation time, but also took the important step of studying the detailed early reflection pattern, including directional information. This was required for a tool that should be used as a practical design tool, whereas previous studies had been research tools to study more generic research questions.

As told by Asbjørn Krokstad, [16], much inspiration for the development of the computerized methods came from the ICA conference paper from 1962 by Schroeder et al, [9]. The PhD work by Asbjørn Krokstad, in Trondheim with Wilhelm Løchstøer as supervisor, was clearly inspired by this presentation. He studied sound fields in an anechoic chamber using the image source method which could represent the reflecting walls. The image source technique was the "archrival" of the ray tracing technique. Even with this experience of the image source technique, ray tracing was employed for the classical 1968 paper, which was submitted in November 1967.

Later developments of ray tracing in room acoustics

After the paper by Krokstad et al was published in 1968, it appeared as if it was unknown for some time, at least to American researchers. In 1973, a paper published by Haviland and Thanedar outlined a method

to compute the detailed response in one specific receiver location using ray tracing – but only for rectangular rooms [20]. Another paper, published in 1977, that also seemed to be unaware of the Krokstad paper, was mentioned earlier [15]. On the other hand, citations of the Krokstad paper appeared in 1971, 1973, [21], and later.

A lot of research has been done to develop the ray tracing technique further. Much work has studied accuracy issues since ray tracing is inherently a stochastic process (as long as there is at least one partly diffusing surface area in a room). The so-called cone tracing was presented by Van Maercke et al, replacing thin rays (hitting a receiver sphere) by propagating cones (hitting a receiver point) [22]. An important development was presented by Vorländer with the so-called hybrid technique: ray tracing was used to find possible reflection paths but in a subsequent phase, the ray-tracing-identified specular reflection paths were replaced by their image-source equivalents. An advantage was that the image source method gives exact reflection paths, which can be used for improved accuracy in the early path of the impulse response [23]. This linking between ray tracing and the image source methods was also explored through the beam tracing technique presented by Walsh, where ray bundles were treated as coherent “beams” [24]. This beam tracing was shown by Stephenson to facilitate the inclusion of diffraction and developments to avoid its computation time explosion [25].

A step towards avoiding the “either specular or diffuse reflection” approach in ray tracing was taken by Dalenbäck where a method let reflections generate both specular and diffuse reflections while avoiding an exponential growth in path number tracing as function of reflection order [26]. The ray tracing technique was combined with another algorithm, radiosity, by Lewers [27]. Later, the Odeon software employed components from radiosity [28].

Ray tracing in other fields

So, was room acoustics the pioneer field for the computerized ray tracing technique? Not really; as early as 1954 examples from optics were published. A paper titled “Ray tracing on the Manchester university electronic computing machine” by Black was published in the British Proceedings of the Physics Society [29]. This was not so surprising – the term ray tracing does after all come from optics. Ray tracing in optics is typically used to study the refraction through optical lenses. Compared to room acoustics the “direct wave” is dominating, and studied in detail, while reflections might be ignored.

On the other hand, the medium is refractive so that the rays do not travel along straight lines.

In underwater acoustics, early work was apparently done on using ray tracing in the US Navy. The abstract in a 1956 report by Anderson and Peterson claims that “*This report discusses: (1) an acoustic intensity program for estimating convergence zone propagation loss using ray theory*” [30]. More publically, in an abstract from an ASA Meeting in November 1961, Norris claimed that “*A ray-tracing program which has been developed for the IBM 704 and 7090 computers yields results which show excellent agreement with experimental data. The program permits ray computations for arbitrary source and receiver depths, bottom profiles, and velocity structures. The tabulated results give actual ray trajectories as well as the geometrical spreading associated with each path.*” [31].

In underwater acoustics, a central problem is that the medium is not homogeneous, which leads to that straight-line rays can not be used (similar to in optics). On the other hand, geometries are practically always 2D, with a flat top surface (the sea surface) and a deterministically shaped bottom profile. Multiple reflections are studied but with more restricted geometries and lower orders of reflection. Of curious interest is also work on so-called analog computers – electronic circuits that performed calculations such as integrations and differentiations, by, e.g., Graber et al in 1961 [32].

Ray tracing has more recently been developed heavily in computer graphics. A paper by Whitted in 1980 is considered as the foundation of ray tracing in computer graphics [33]. This kind of ray tracing was similar to the one in acoustics, except that rays were “shot” from a receiver’s eye, through a grid of pixels that represent the display, reflected off surfaces, and finally reaching light sources. The more acoustics-like approach of emitting rays from (light) sources is usually called “global illumination” in graphics. Because of the general interest of computer graphics, many researchers are active in this field and the techniques are developed rapidly. This can be illustrated by the fact that the classical first paper on ray tracing in graphics, [33], has been cited 240 times (by June 2008) according to the journal citation database *ISI Web of Science*SM. In addition, the hardware for computer graphics generation (graphics processing units, or GPUs) has recently been developing at a faster pace than general CPUs for computers. This has lead to that so-called general-purpose GPUs have been developed, that can be used as numerical co-processors for many kinds of numerical calculations with processing

power many times higher than CPUs [34]. Acoustical ray tracing has been demonstrated on such GPGPUs [35], [36].

A last field where ray tracing has become a common tool is the study of radio wave propagation, indoors and outdoors in city environments. This application applies specular reflections (as in room acoustics) as well as transmission, and of multiple orders. An early paper on this technique was published in 1991, [37]. It could be noted that diffraction over edges has been employed in radio propagation studies for a long time, either based on classical Fresnel diffraction, or based on the high-frequency asymptotic geometrical theory of diffraction (GTD) that was presented by Keller [38].

The inclusion of diffraction modelling in room acoustics ray tracing has been suggested too, and offers an interesting combination of the wave-oriented diffraction modelling with the geometrical acoustics-based ray tracing, where energy-based superposition is the basis [39], [40].

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