1. **Room acoustic simulation**
   1. **Introduction**

Almost all the deterministic simulation models of Geometrical Acoustics (GA) are based on physical model of image sources (this model is completely described in previous sections) and only diﬀer in the way how image sources are identiﬁed. There might be two ways to define the image sources by using either forward (i.e. ray) tracing or reverse construction. Different algorithm are, for instance hybrid ray tracing, beam tracing, pyramid tracing, frustum tracing, and so forth are in use. Image Source methods are a very good approximation for perfectly reﬂecting or low-absorbing surfaces in large rooms with large distances between the sound source, wall, and the receiver [**1**]. Round robin tests of room acoustics simulation by [**2**] revealed the drawback of the IS-method. In the temporal development of the RIR, however, scattering is a dominant eﬀect already from reﬂections of higher orders (e.g. of order two or three) which cannot be neglected, even in rooms with rather smooth surfaces [**3**]. From this it follows that pure image source modelling is perfectly qualiﬁed for determining the direct sound and the early reﬂections, however, it does not yield satisfactory results for the late part of the room impulse response. Solutions to the problem of scattering are either stochastic Ray Tracing (RT) or radiosity methods. The fast radiosity methods are based on the irradiation and re-radiation of sound energy among surface elements in order to calculate the total energy density at a receiving point via direct and reverberant paths [**3**]. Here, ideal diﬀuse reﬂections are assumed meaning that the directional pattern of arriving sound is equally distributed over all directions and the energy decreases exponentially with time. In addition, and with regard to auralization, the level, direction of arrival, and temporal distribution of late arriving reﬂections have a strong inﬂuence on the listener’s spatial impression and should therefore not be randomized. Fortunately, all these limitations do not apply for stochastic RT, which is a Monte Carlo method for computing the quantized energy envelope of the RIR. This envelope comes in a time and frequency dependent energy histogram where the size of both time slots and frequency bands are orientated on the human hearing.

* 1. **Stochastic Ray Tracing**

Stochastic RT emulates the propagation of a sound impulse from a sound source by means of energy particles which travel as discrete rays, get reflected from the geometric objects and are detected by receivers in order to compute the respective energy envelope of the RIR as described in Figure 2.1. The simulation starts by emitting a finite number of particles that are evenly distributed on the source’s surface and travel with the speed of sound which can be derived from the room temperature, humidity and air pressure [**4**]. Each particle carries a certain amount of energy that is dependent on the source’s directional pattern. During propagation each particle loses energy because of air absorption and reflections from the surface material dependent on absorptions and scatterings properties of that material. These reflections are either specular or diffuse. Which means that these reflections are either reflected at the angle of reflection which is equal to the angle of incident or scattered at random directions. This is scattering is decided by comparing a random number between zero and one with the scattering coefficient, denoted by of the object with which the particle collides.

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| **Figure 2.1(a):** Visualization of propagation energy particles within a room [**1**] |
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| **Figure 2.1(b):** Illustration of scattering of energy into specular patterns (**left**) and an example of three energy particles propagating in room and detected by detector (**light**) [**2**] |

The scattered energy is usually assumed to be distributed according to Lambert’s cosine law, i.e., the intensity of a reflected particle on an ideal diffuse scattering wall is independent of the angle of incident but proportional to the cosine of the angle of reflection [**3**]. However, angle dependent energy distributions are also applicable and should be used to describe special types of geometries that scatter in a preferred direction. As it follows from the definition of the scattering coefficient the factor has to be taken into account for the energy attenuation of each particle in addition to the absorption coefficient . Therefore, the energy of the particle is weighted with if the reflection is diffuse and with if the reflection is specular as illustrated in Figure **2.1(b)**. Each particle is traced until a predefined termination condition is fulfilled (i.e. exceeded simulation length or under-run of a minimum particle-energy threshold). In contrast to the image source method the receivers are represented by detectors that have either a volume or a surface. When a particle hits a detector the current particle’s energy, angle of incidence, and time taken are stored in respective entry of the detector’s particle histogram. The histogram is organized as a clustered container of time slots , where the size of should be orientated on the time resolution of the human hearing and the desired relative energy variance which is described in Figure **2.2**. Hence, should be selected in the range of few milliseconds whereby the detection resolution can be reduced over time allowing greater for the late part of the impulse response and vice versa [**3**].

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| **Figure 2.2:** a) Free field propagations and distance law by counting, b)Tracing a ray from source to detector and c) creating an impulse response by counting events [**2**] |

As the material properties (i.e. absorption and scattering coefficients), directional patterns of source and the energy attenuation by air is strongly frequency dependent RT can only be performed for a certain frequency. Thus, a complete RT comprises not only one but several cycles where the central frequencies of either octave bands or one-third octave band are usually chosen as simulation frequencies resulting in 10 and 31 cycles respectively to cover the audible frequency range. From this point, we receive a three dimensional histogram from the ray tracing simulation with time slots of length on the abscissa, the frequency bands on the ordinate and the time and frequency energy on on the applicate. These values can either be seen as temporal energy distribution for a certain frequency band or as short-time spectral energy density for a time slot .

* 1. **Room Impulse Response Synthesis**

As we learnt from the previous section that a detector’s energy histogram represents only the energy envelope of room impulse response (RIR), whereas, many room acoustical parameters, for example reverberation time and clarity, are calculated from such histograms. Therefore, the RIRs cannot be applied directly to the auralization because of the lack of an appropriate temporal resolution. However, the RIR’s temporal fine structure can be synthesized well by means of a Poisson-distributed-noise process as described in [**5**]. Assuming a sound reflection as an event the probability of the occurrence of events in a time interval is given by Equation **2.1**.

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|  | **(2.1)** |

Where, denotes the mean event occurrence. On the other hand, a time interval of two consecutive events of a temporal Poisson process is exponentially distributed and the associated density distribution follows [**6**].

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|  | **(2.2)** |

Using this equation, the interval size can be derived as a function of a uniformly distributed random number , leading to Equation **2.3**, for .

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|  | **(2.3)** |

Where the mean event occurrence μ relates to the mean reflection density of the room with . Based on this equation, the noise process can be synthesized by using Dirac delta functions with constant magnitude as random events. Starting at a time , which describe the minimum between , the sequence of Dirac deltas is consecutively generated using Equation **2.3** until a maximum length is reached. In order to adapt to the sampling frequency of the RIR the Dirac deltas are optionally signed counting Dirac deltas positive and negative in the temporal first and second half of a sample respectively and restricting the number of Dirac deltas per sample to one. Furthermore, can be kept at a maximum of without generating acoustical artifacts such as rattling. In the following these sequences of Dirac deltas are the basis for constructing both monaural and binaural RIRs.

* + 1. **Monaural Room Impulse Response**

For real-time auralization the monaural RIR can efficiently be constructed by pre-processing band pass filtered Dirac delta sequences that are weighted with the simulated energy envelope of the RIR. For this Dirac delta sequence is transformed to frequency domain, as shown in Figure 5.17, and filtered by asymmetrical high pass and low pass combination with different slope and shape of a Raised-Cosine-Filter with following Equation **2.4**.

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|  | **(2.4)** |

Where denotes central frequency of the frequency band and and describe the lower and upper limit of the frequency bands respectively. Afterward, the filtered spectrum is transformed back to time domain resulting in band pass filtered Dirac delta sequences . As long as volume of the room does not change drastically these sequences have to be computed only once which can be accomplished during a pre-processing step of the simulation.

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| **Figure 2.3:** Construction of a monaural RIR [**1-2**] |

The monaural RIR can now be quickly constructed by weighting sample wise with Equation **2.5**, where denotes the length of the histogram’s time slot, the value of the sample of , the sampling frequency the band width of regarded frequency band , and the energy of the histogram’s time slot that relates to the sample. In a final step, summing up all weighted noise sequences in time domain leads to the overall monaural RIR, given in Figure **2.3**.