Sounds out in the open, distance $r$ away from sound source:

Sound Intensity

$$I(r) = \frac{\text{Power}}{4\pi r^2}$$

Intensity, $I$ in Watts/m$^2$ (since SI units of Power are Watts)

Sound intensity decreases as $1/r^2$ — spreads out radially in all directions from sound source

- Sound Intensity Level $L_I(r) = 10 \log_{10} \left( \frac{I(r)}{I_o} \right)$ decreases by 6 dB for each doubling of $r$.
- Objects on ground (grass, weeds, bushes, etc.) absorb sound energy...
  ⇒ Sound intensity $I(r)$ falls off faster than $1/r^2$ (i.e. $L_I(r)$ falls off more steeply than 6 dB)
- Put a reflecting surface behind musicians for focusing sound to audience...

- Confined sound in a 3-D enclosure (e.g. a room):
  - Get sound reflections off of walls/floor/ceiling (just like light bouncing off of mirrors)
  - Angle of incidence = Angle of reflection at wall/floor/ceiling...
  - Law of reflection (light and/or sound) arises from energy/momentum conservation at wall/mirror!

**Fig. 1.** Multiple reflections from the walls of a room of a single impulse produced by a sound source.
Reverberation/Reverberant Sound:

— Consists of the direct sound, multiple echoes and “clutter”:

Reverberation Time, $T =$ time for sound to decay to $10^{-6}$ (one millionth) of its original intensity, $I$. Corresponding change in Loudness Level/SPL: $\Delta L = 10 \log_{10} \left( \frac{I_2}{I_1} \right) = 10 \log_{10} (10^{-6}) = -60 \, dB$.

Reverberation time also known as $T = T_{60}$.

Reverberation Time, $T \propto$ (= proportional to) room volume, $V$ — i.e. $T \propto V$

Reverberation Time, $T \propto 1/Area$ of “hole(s)” in room, $A$ — $T \propto 1/A$

Sabine Equation: $T = K \frac{V}{A}$ where $K =$ constant of proportionality = $T \frac{A}{V}$

If we know $V$ and $A$ and then measure $T$, we find $K = 0.049$ (= universal number!!!)
Sabine Equation

\[ T = K \frac{V}{A} \text{ (seconds)} \]

- \( V \) = Room volume in \( ft^3 \) (\( m^3 \))
- \( A \) = Effective “hole” area in \( ft^2 \) (\( m^2 \))
- \( K = 0.049 \text{ in } \frac{s}{ft} = 0.161 \text{ s } \frac{m}{m} \)

Reverberation Time, \( T = T_{60} = 0.049 \left( \frac{V \left( ft^3 \right)}{A \left( ft^2 \right)} \right) = 0.161 \left( \frac{V \left( m^3 \right)}{A \left( m^2 \right)} \right) \) seconds

= time for sound to decay to \( 10^{-6} \) of its original intensity

If the room physically has no holes in it, the area \( A \) represents the effective area of the room that behaves as if it were a hole, due to sound absorption.

1 \( ft^2 \) =1 absorption unit = sabin or: 1 \( m^2 \) =1 metric absorption unit = metric sabin

Suppose a room with volume \( V \) has a surface area \( S \) made up of same material on all 6 sides:

Total surface area of room \( S \):

\[ S = S_1 + S_2 + S_3 + S_4 + S_{\text{top}} + S_{\text{bottom}} \]

\[ A = aS \]

\[ a \equiv \frac{A}{S} \]

\[ a = 0 \Rightarrow \text{no sound absorption (no “hole”, i.e. } A = 0 \)\]

\[ a = 1 \Rightarrow \text{total sound absorption (“hole” = room area, i.e. } A = S \text{!!}) \]

For a more complicated/realistic room:

\[ A = a_1S_1 + a_2S_2 + a_3S_3 + a_4S_4 + \ldots + a_NS_N = \sum_{n=1}^{N} a_nS_n \]

for \( N \) objects (surfaces) in room.
The “Optimum” Reverberation Time:

— if reverberation time is too short, room sounds “dead”
— if reverberation time is too long, room sounds muddled/obscured

Max Intensity $I_{\text{max}} = P/A$

$P$ (Watts) = acoustic power
$A$ ($m^2$) = total absorption

Suppose e.g. we input a known amount of acoustic power $P = 1$ Watt into a room, we allow time for the sound to build up to a steady level, and then use an SPL meter to measure the max SPL (in $dB$) in the room. We find (i.e. measure) max $dB = 99.54$.

We then invert the $dB$ formula: max $dB = 10\log_{10}(I_{\text{max}}/I_o)$ to obtain: $I_{\text{max}} = 10^{9.954} I_o = 0.009$ $W/m^2$.

Thus:

$$A = \frac{P}{I_{\text{max}}} = \frac{1 \text{ Watt}}{0.009 \text{ $W/m^2$}}$$

$= 110$ square meters

$\simeq 1200$ square ft ($= 1200$ absorption units)

⇒ Can measure the absorption $A$ of any room using this technique!
The “Optimum” Reverberation Time:

The optimum reverberation time is subjective!
- tempo dependent
- sound level dependent
- complexity dependent
- frequency dependent

Calculation of Reverberation Time

Note the frequency dependence of the absorption coefficients for various building materials!
Example Calculation of Reverberation Time, $T = T_{60}$:


With this information, let us calculate the reverberation time of a hypothetical auditorium, which we will arbitrarily assume to be 100 ft long, 60 ft wide, and 40 ft high. The calculation will be for a frequency of 500 hertz. The walls and ceiling will be assumed to be plaster, with an absorption coefficient of 0.10, and the floor covered with carpet on felt, with an absorption coefficient 0.40, as given in Table I. The total absorption is then calculated from Eq. (7) as follows:

<table>
<thead>
<tr>
<th>Area, sq ft</th>
<th>Abs. Coeff.</th>
<th>Abs. Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>100 × 60</td>
<td>6000</td>
</tr>
<tr>
<td>Ceiling</td>
<td>100 × 60</td>
<td>6000</td>
</tr>
<tr>
<td>Two side walls</td>
<td>2 × 40 × 100</td>
<td>8000</td>
</tr>
<tr>
<td>Two end walls</td>
<td>2 × 40 × 60</td>
<td>4800</td>
</tr>
</tbody>
</table>

Total absorption \( \approx 4300 \) units.

The volume of the room is \( 40 \times 60 \times 100 = 240,000 \) cubic feet. The reverberation time will then be

\[
T = 0.049 \times \frac{240 \times 10^3}{4300} = 2.7 \text{ sec} \quad \text{Too long!}
\]

If \( T \leq 1.5 \) sec, then:

\[
A \geq 0.049 \frac{V}{T} = 0.049 \frac{240 \times 10^3}{1.5} = 7800 \text{ ft}^2 (= \text{Abs. units})
\]

If 4300 absorption units already present, then we need to add: \((7800 - 4300) = 3500 \) units

1” thick perforated tiles have an absorption coefficient, \( a = 0.70 \) (@500Hz)

\[
A = aS = 3500 \text{ ft}^2
\]

\[
S = \frac{A}{a} = \frac{3500 \text{ ft}^2}{0.70} = 5000 \text{ ft}^2
\]

⇒ Need a physical area of 5000 ft\(^2\) of 1” thick perforated tiles.

— Need to be careful here: seats, people, etc. are sound absorbing too!!!

— Acoustical properties of an empty auditorium are not the same as when full!!!
Air also absorbs sound – *i.e.* air temperature & relative humidity also matter!

Taking into account air absorption, the Sabine Equation is modified as:

\[
T = 0.049 \frac{V \left( \text{ft}^3 \right)}{A \left( \text{ft}^2 \right) + mV \left( \text{ft}^3 \right)} = 0.161 \frac{V \left( \text{m}^3 \right)}{A \left( \text{m}^2 \right) + mV \left( \text{m}^3 \right)}
\]

where \( m \) is a temperature, humidity and frequency-dependent parameter, varying from \( m \approx 0.01/m \) at 2 KHz to \( m \approx 0.1/m \) at 8 KHz for ~NTP conditions with \( RH \approx 30-50\% \).

Nowadays, all of this is done using acoustical computer simulation programs (*e.g.* EASE, LARA), all “tuned” from real measurements. Input all of the gory details of shape, size, and volume of rooms, exact shapes, sizes, and locations of all sound absorbing elements, *etc.* (also frequency dependence – see figure below)!

![Diagram](image)

**Fig. 6.** Recommended variation of reverberation time with frequency.

Again, “Recommended” ⇒ subjective decisions were made about this….
Auditorium Background Noise:

Ambient/background noise levels in auditoriums/concert halls – e.g. from noise sources such as ventilation systems, nearby traffic, etc. needs to be controlled such that it does not detract (or distract) from the audience’s enjoyment of the music performance. Poorly designed ventilation systems often generate ~ 1/f type noise (or even resonances!) as well as broad-band noise from air flow in ducts and through grilles. Inadequate isolation from corridor noise, noisy and/or squeaky doors, etc. can also contribute unwanted sounds.

Over the years, Noise Criteria (NC) curves have been developed that specify maximum permissible noise levels in octave frequency bands for a particular noise rating. A specification for NC-20 (or below) requires octave-band sound pressure levels $SPL$ (in $dB$) at or below the NC-20 curve shown in the figure below (n.b. which closely follow the Fletcher-Munson apparent loudness level curves):
A good concert hall should at least meet the NC-20 curve, and preferably the NC-15 curve. For lecture halls and classrooms, the noise levels should be at (or below) the NC-30 curve, or better yet, the NC-25 curve. $T_{60}$ reverberation times should also be $< 0.5$ seconds in lecture halls and/or classrooms, in order to avoid speech interference problems, particularly in the speech intelligibility range of $500 - 4000$ Hz. A teacher using a normal voice will produce a sound pressure level of $\sim 46$ dB at the ears of a student $30$ ft away; the NC-30 curve corresponds to an average background noise level of $\sim 36$ dB in this frequency range, thus a $10$ dB difference in speech vs. noise level, as required for speech intelligibility.

Today, audio/acoustic engineers can harness the power of the computer and use sophisticated computer programs to create accurate 3-D simulations of the acoustical environment/acoustical properties of an arbitrarily-shaped room – be it a concert hall, a theatrical stage, a church, etc. Ray-tracing techniques are used to simulate 3-D sound propagation from accurately-modeled sound sources, or even actual recorded sounds, reflecting off of the 3-D surfaces of the room, including frequency-dependent absorption and diffusivity coefficients of these surfaces.

The most common measure of the reverberation time for these programs is $T_{30}$, (the time for the sound intensity to decay to $1/1000^{th}$ of its steady-state value – noting that $T_{60} = 2 T_{30}$) which is calculated from the slope of the curve fit through the simulated ray-tracing generated reverberation time data for the sound intensity level vs. time as the sound intensity level decays from $-5$ dB to $-35$ dB. The $T_{30}$ reverberation time obtained in this manner is a more sensitive indicator of the true reverberation properties of a room than that obtained from the Sabine equation, because it takes into account both the absorption and the diffusivity of the room surfaces, as well as the detailed specifics of the geometry of the room (limited only by the accuracy input to the 3-D model of the room). In such acoustics ray-tracing programs, one can also investigate $T_{30}$ e.g. in different octave bands (i.e. as a function of frequency) much more easily than $T_{60}$, which requires significantly more computation time.

Speech intelligibility is another important acoustical attribute of a room, particularly for theater and church-goers - any rooms or acoustical environments where public speeches are important. A statistic for speech intelligibility is $D_{50}$, which is defined as the ratio of the integral of the square of pressure over the first 50 milli-seconds of the initiation of sound associated with e.g. a very short sound impulse to that integrated over all time for that same sound, expressed as a percentage:

$$D_{50} = 100 \times \left[ \frac{\int_{t=0}^{t=0.050s} p^2(t)\,dt}{\int_{t=0}^{t=\infty} p^2(t)\,dt} \right]$$

Thus, $D_{50}$ is a measure of the per-cent total sound energy arriving within 50 msec after an initial pulse of sound. If most of the energy of the sound impulse is within this 50 msec window, then it will be {much} easier for people in this room to understand speech than if e.g. there are many echoes over a longer time for people to try to comprehend. This sound parameter can only be determined (reasonably easily) with ray-tracing acoustical simulation software, for a realistic room. Obviously, it can be measured in a real room, one that already exists.
Ray-tracing acoustical simulation software programs can also obtain accurate estimates of the sound pressure levels everywhere in the simulated room (and as a function of frequency) to enable the \{as uniform as possible\} sound pressure levels independent of the location of a person in the room, thus eliminating and/or minimizing dead spots or hot spots in the room.

Please see/read the P193POM Lecture Note hand-out on “EASE Examples” for more details.
Legal Disclaimer and Copyright Notice:

Legal Disclaimer:

The author specifically disclaims legal responsibility for any loss of profit, or any consequential, incidental, and/or other damages resulting from the mis-use of information contained in this document. The author has made every effort possible to ensure that the information contained in this document is factually and technically accurate and correct.

Copyright Notice:

The contents of this document are protected under both United States of America and International Copyright Laws. No portion of this document may be reproduced in any manner for commercial use without prior written permission from the author of this document. The author grants permission for the use of information contained in this document for private, non-commercial purposes only.