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NPTEL ONLINE CERTIFICATION COURSES

NPTEL

Architectural Acoustics

Lecture 1: Introduction and historical overview

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Course Structure (8 modules- 40 lectures)

Module		Instructor	No. of lectures	Total Duration (hrs)
1.	Sound Physics	SG, SPB	5	2.5
2.	Room acoustics and reverberation	SG, SPB	5	2.5
3.	Sound absorption	SG	5	2.5
4.	Acoustical criteria of space design	SG	5	2.5
5.	Design principles of auditorium	SG	5	2.5
6.	Electro-acoustics and open-air auditorium	SG, SPB	5	2.5
7.	Air and structure borne sound propagation	SPB	5	2.5
8.	Environmental acoustics	SPB	5	2.5

Definition

"Acoustics" is derived from the Greek word **ἀκουστικός** (akoustikos), meaning "of or for hearing, ready to hear"

- is a branch of physics
- deals with study of all kinds of mechanical waves in any medium
- It was Aristotle who first established the relation that anything that vibrates can produce sound dates back to (384–322 BC).
- Architectural acoustics recognised as a science just over a century

Architectural Acoustics

- The scientific knowhow to achieve a **good sound within a space** (building)
- Involves the study of speech **intelligibility**, speech **privacy**, music **quality**, noise control and **vibration reduction** within the built environment.

HISTORICAL INTRODUCTION

Overview

- Earliest meeting places were open areas in natural forms

  Epidaurus 330BC, Flavian Amphitheatre 71AD,Circus Maximus, Hippodrome
- Understanding of the directional nature of human voice
- Seating arrangements were made in concentric semi-circles in front of speakers for best audibility

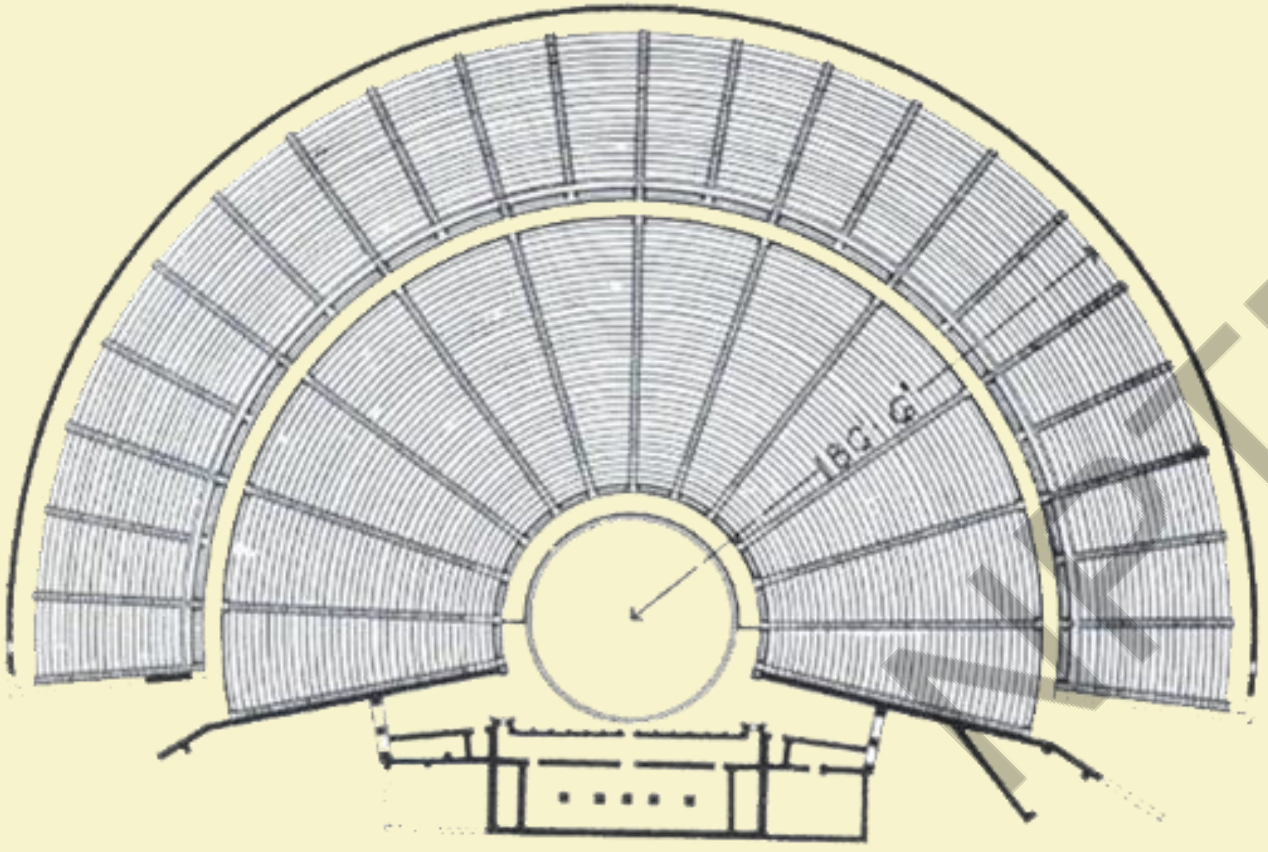
Early Greek

- Earliest outdoor amphitheaters
- Seating plan: segmented circle, more than 180°, mostly on hill-sides facing the sea.
- Theories followed: wind carried the sound, specific material requirement
- Steeply raked seats, low background noise

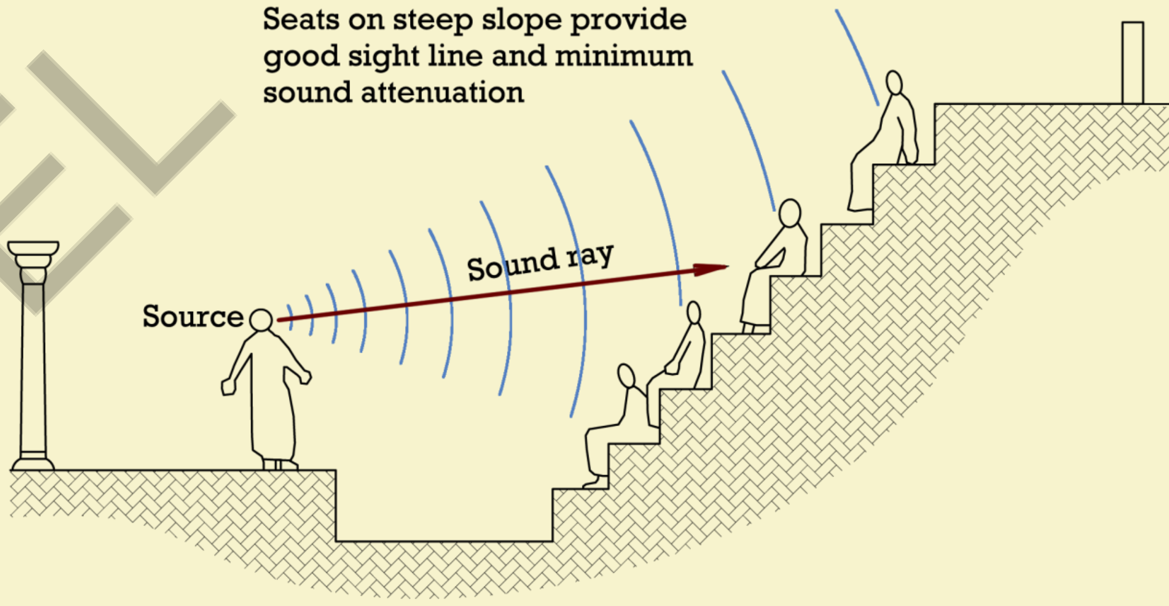
Resulted in increased intelligibility (clarity)

Greco-Hellenistic theater, Epidaurus 330BC

Source: Wikimedia Commons



PLAN



Plan and section: during Greek period

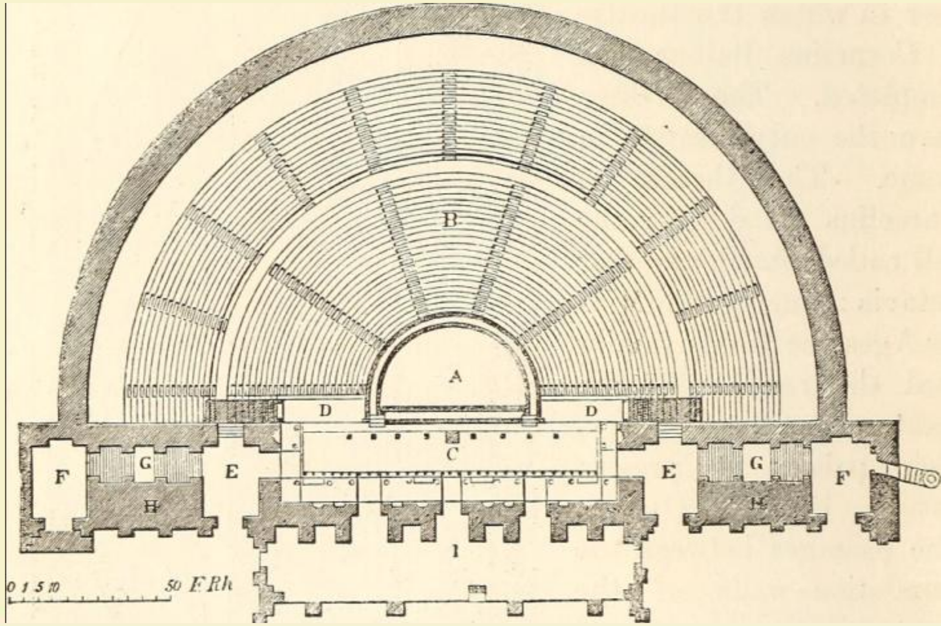
Source: Wikimedia Commons

Early Roman

- Seating arc limited to 180°.
- Used arch features instead of hill slopes
- Added a stagehouse (*skiene*) behind the actors, a raised seating area (*proskenion*), hung awnings (*valeria*) to shade the patrons

 Ex: Aspendius Roman theatre, Turkey

Typical plan during Roman period



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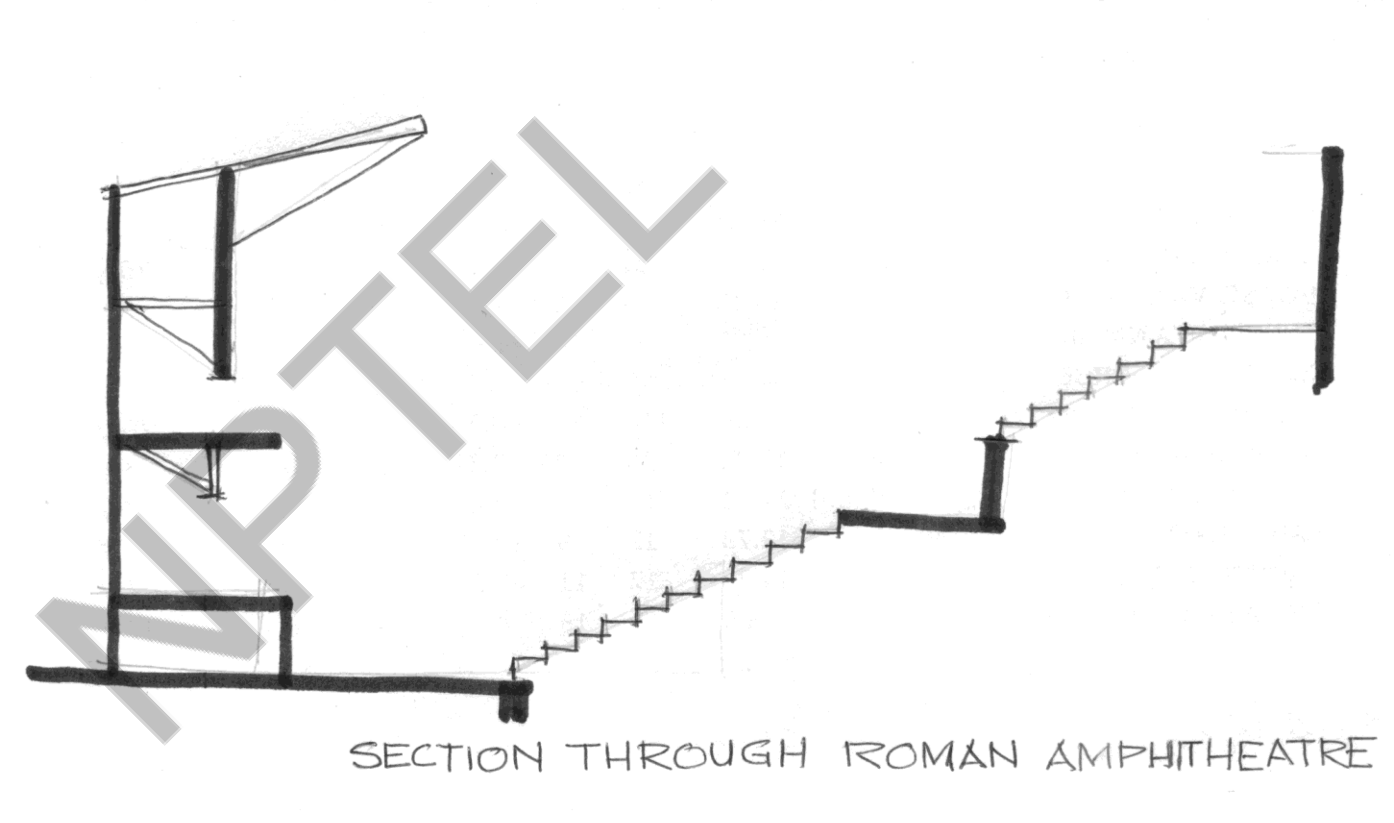
Early Roman



Early Roman

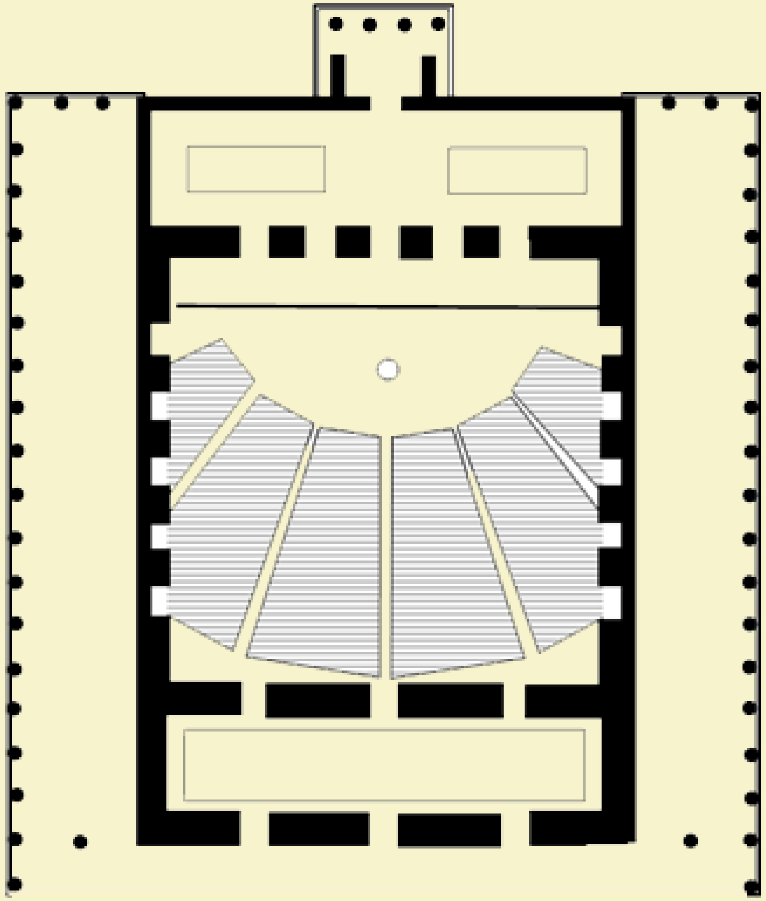
Flavian Amphitheatre 71AD (Capacity - 40,000)

The Colosseum, Rome *Source: pixabay.com*

Public Domain, https://commons.wikimedia.org/w/index.php?curid=175419

Early Roman

- Smaller theatres (odea)- built for dramas/plays (dialogues)
- Examples-Odeon of Agrippa, 12BC



PLAN

Source: Wikipedia

Vitruvius Pollio, Book: De Architectura (27BC)

- Seating should not face South (audience should not be looking at the Sun)
- Unrestricted sightlines to be maintained
- Open mouths of Large sounding vases to be placed centered on cavities on wedges such that the mouth is exposed to the stage for improved sound quality

Early Christian Period 400 – 800AD

- Basilican church of St. Peter, Rome, 330AD.
- High central nave with two parallel aisle on either side.
- Aisles separated by colonnade which supported upper walls.
- Low pitched roof, ending in an apse.
- Preceded by atrium.

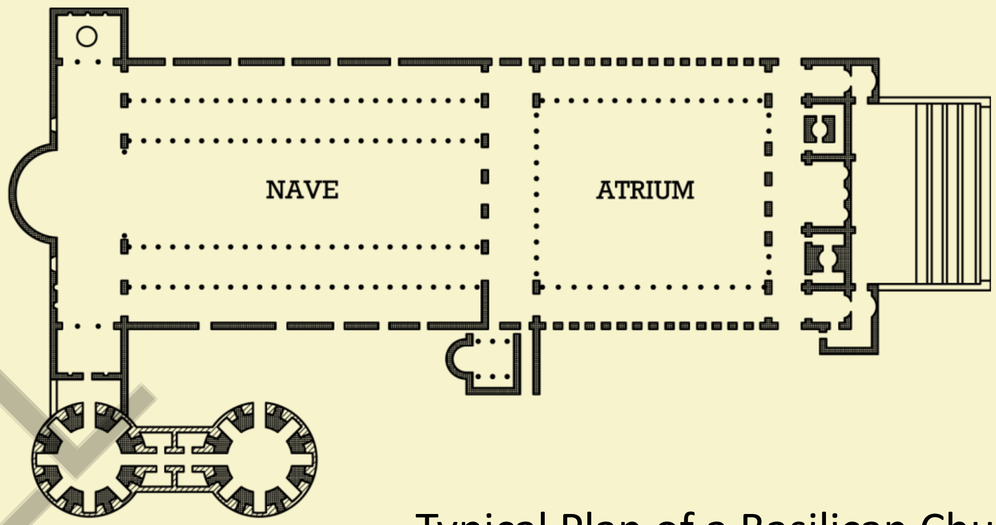
Model for later church construction.

Source: Wikimedia Commons

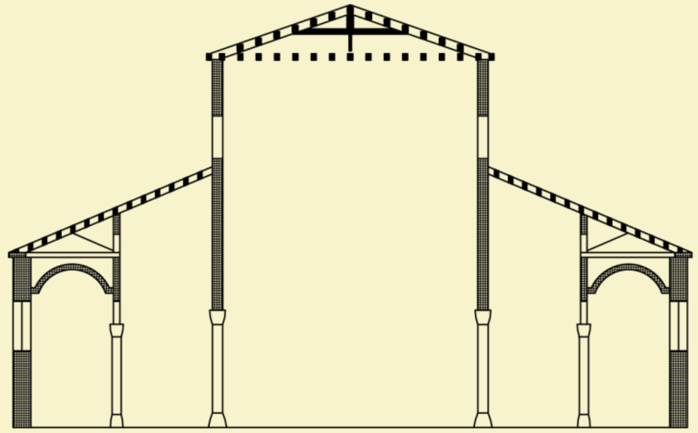
Source: pxhere.com

Early Basilican churches

- **Highly reverberant**
- Pace and form of music had to **adjust to the architecture** to be comprehended.
- The simple melodic line, the sound blending from chants in such spaces were beautiful.



Typical Plan of a Basilican Church



Typical section of a Basilican Church

Eastern Roman

- Hagia Sophia, Istanbul (537AD)

- Enormous dome, spanning 33 meters (107 feet) in diameter
- Set in the centre of a 76 meter (250 foot) long central nave.

- Dissipative forms adopted to disperse the sound

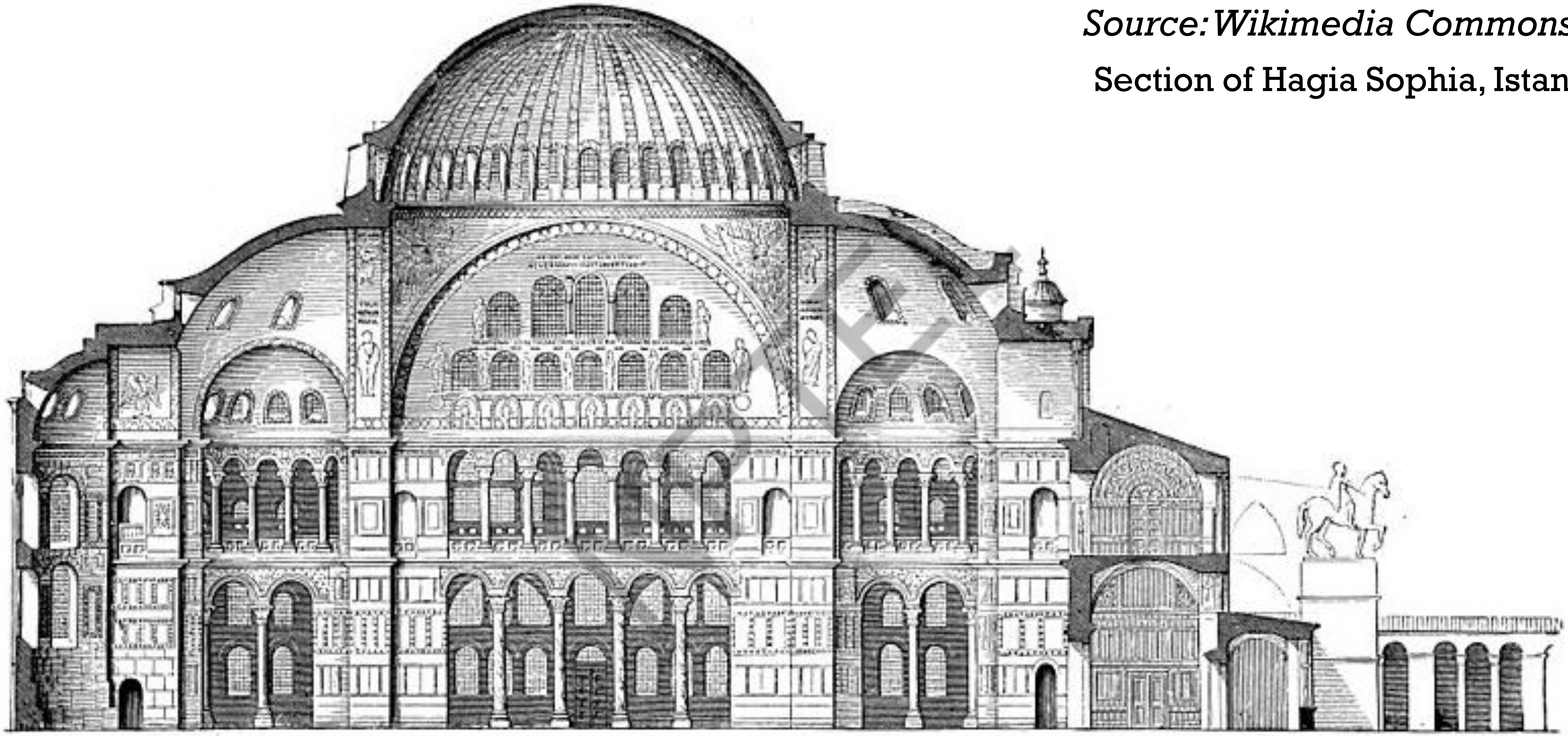
- Stalactites at the corners to disperse sound

- Use of tow, a plant fibre, in plaster to absorb some and rebound sound

Interior of Hagia Sophia, Istanbul

Source: Wikimedia Commons

Source: Wikimedia Commons



Source: Wikimedia Commons

Section of Hagia Sophia, Istanbul

Source: Wikimedia Commons

Romanesque and Gothic Cathedrals (800 – 1100 AD)

Notre Dame Cathedral, Paris

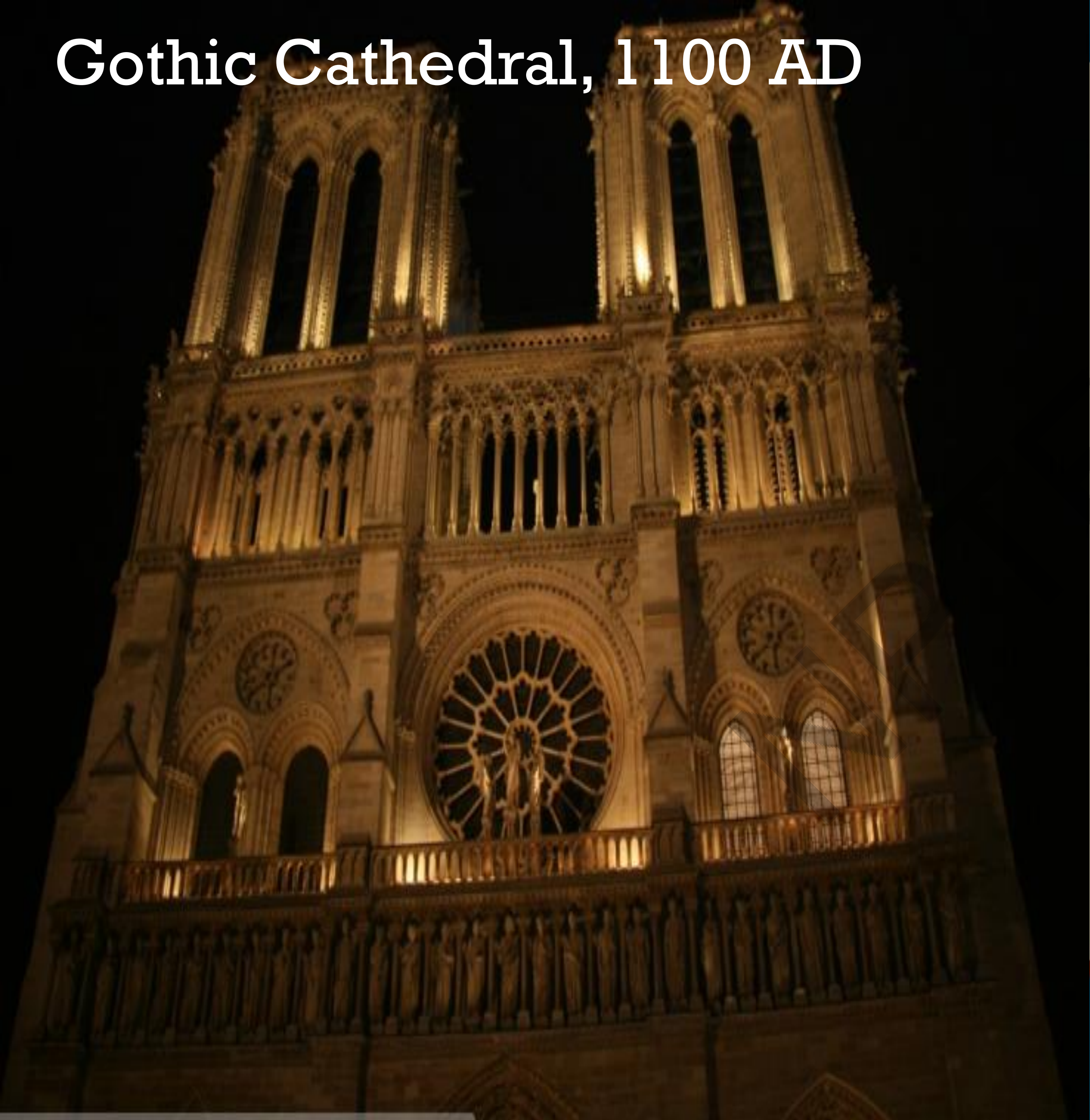
•art and engineering of working in stone

•vaulted naves, over 30 meters (100 feet) high

•lightened with windows and open colonnades

Plain chant was the music of the religious orders and was suited perfectly to the cathedrals.

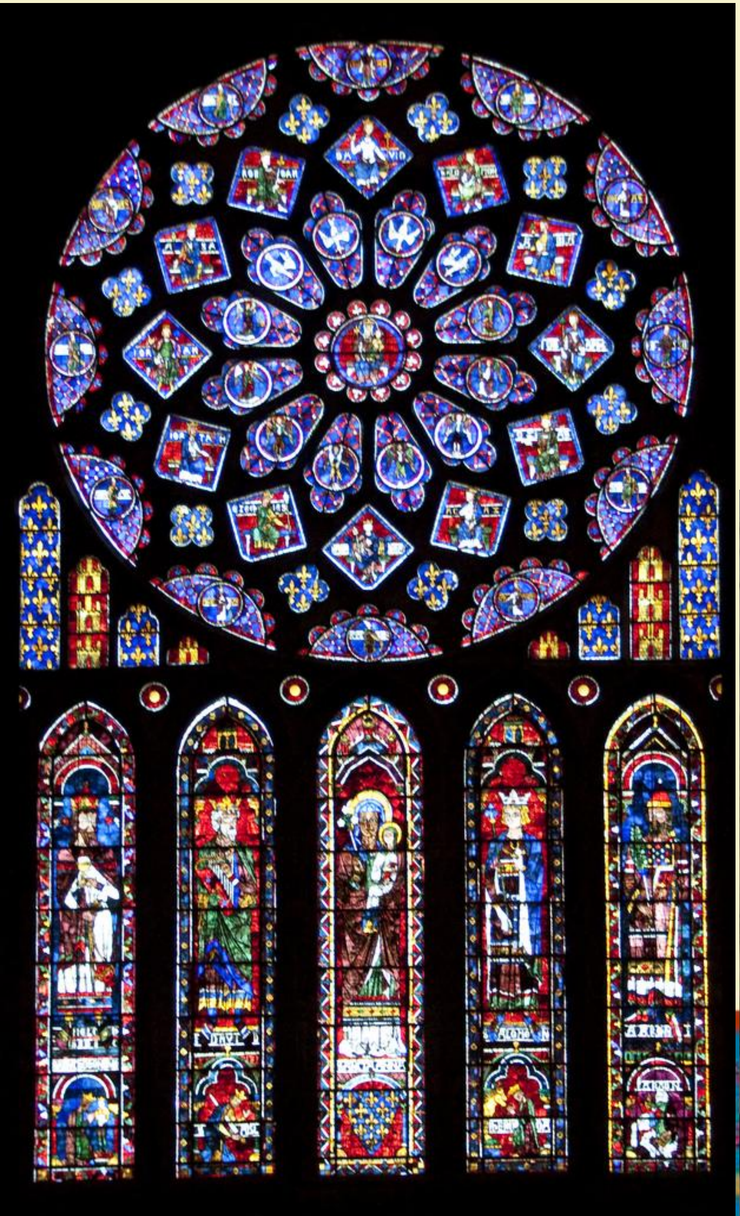
Gothic Cathedral, 1100 AD



Cathedral of Notre Dame

Source: Wikimedia Commons

Rose-glass windows



The Suleymaniye Mosque Istanbul (1558)

The series of openings in the dome present for sound absorption

Mimar Sinan, the Architect avoided using regular forms like a perfect square or cube, and used niches, buttresses, galleries, etc. to break regularity.

Renaissance (14th to 17th)

Rise of towns and commerce, public entertainment became more secular
less of religious in focus

Plays and theatres

Semi-elliptical seating plan of Romans was pushed back into a 'U' shaped seating.

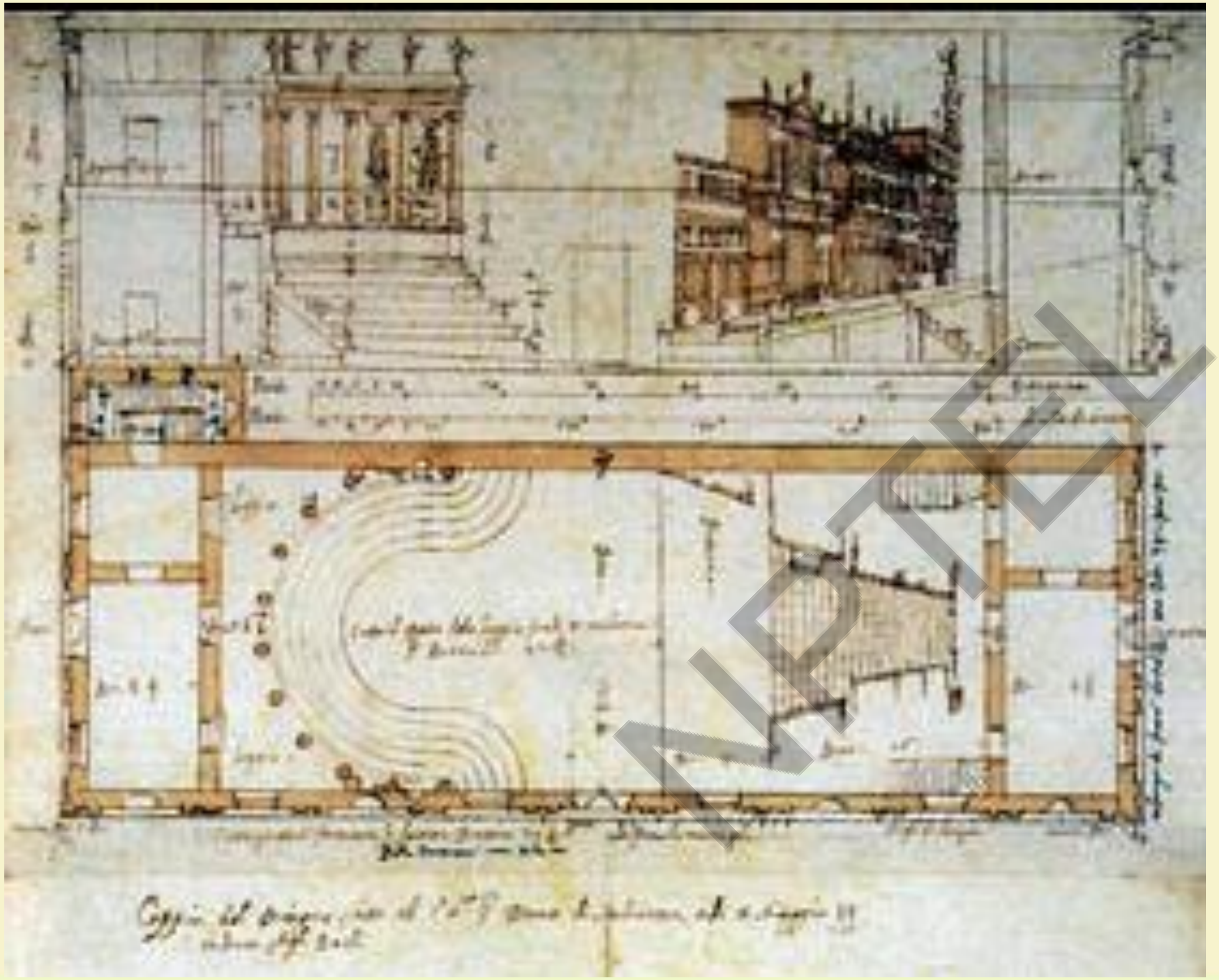
Little acoustical support in halls

Italian Opera Houses
Truncated elliptical seating

Teatro Olimpico, Vicenza, Italy

Source: Wikimedia Commons

Renaissance



Typical seating plan

Source: Wikimedia Commons

Baroque (17^{th} – 18^{th})

Baroque theatres

Baroque era instrumental music

Theatro-Farnese, Parma, Italy *Source: Wikimedia Commons*

Baroque (17^{th} – 18^{th})

Theatro Santi Giovanni e Paolo, Venice

Source: Wikimedia Commons

Classical (18^{th} – 19^{th})

------a revival of visual and performing arts and music concerts (Haydn, Mozart & Bach, Bethoven)

Shoebox halls: high ceilings, multiple diffusing surfaces, and low seating capacity

Hanover Square Room, London

Altes Gewandhaus, Leipzig, Germany

Source: Wikimedia Commons

Shoebox Halls

Stadt-casino Basel, Switzerland

Altes Gewandhaus, Leipzig, Germany

Grosser Musikvereinssaal, Vienna

Source (All) : Wikimedia Commons

Concertgebouw, Amsterdam, Netherlands

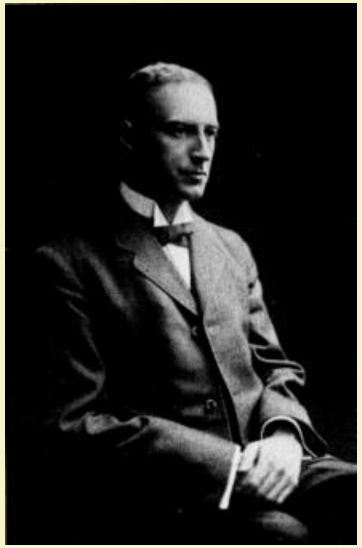
Beginning of Architectural Acoustics

Knowledge of the acoustical behavior of rooms had not yet been set out in quantitative form.

Successful halls were designed using incremental changes from previously constructed rooms.

It was all experimental - termed as 'bizarre science' by the Architect of Paris Opera House.

Acoustical correction of Fogg Lecture Hall(1896)



Theoretical beginnings of architectural acoustics started by the young physics professor at Harvard College

Father of Acoustical sciences: Wallace Clement Sabine (1868–1919)

Key discovery was that the product of the total absorption and the reverberation time was a constant.

Source: Wikipedia

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Books and sources:

Concepts in Architectural Acoustics, M. David Egan, Publisher: McGraw-Hill Inc.

Architectural Acoustics by M. Long, Elsevier Academic Press

Acoustics Of Gothic Churches, PACS reference: 43.55 Gx

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Architectural Acoustics

Lecture 02: Introduction to Architectural Physics

Dr. Shankha Pratim Bhattacharya
Department of Architecture & Regional Planning

Learning Objective

- Develop the basic understanding of sound propagation
- Establish the fundamental parameters of sound wave from generalised wave equation

Types of Acoustics

- Acoustics
  - Wave Acoustics
  - Ray or Geometric Acoustics
  - Statistical Acoustics

Study of Acoustics

Architectural Acoustics → **Indoor/Room Acoustics**

Architectural Acoustics

↓

Outdoor Acoustics/ Open-air Acoustics

↓

Environmental Acoustics

- Noise Control
- City Planning
- Acoustics and Landscape

Indoor/Room Acoustics

↓

Building Acoustics

- Design Fundamental
- Acoustical Material
- Noise Reduction
- Indoor Acoustical Quality
- Sound Transmission
- Mechanical Vibration Control

Definition of Sound

Objective / Physical Definition

Sound is a form of energy. It travels in waves through elastic media and causes fluctuation of pressure and particle displacement.

Sound is an auditory sensation produced by stimulation of the organ of hearing, evoked by physical fluctuation of pressure in media.

Subjective / Physiological Definition

Longitudinal Wave

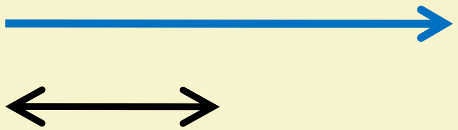
In a *Longitudinal Wave* the particle displacement is parallel to the direction of wave propagation.

In a *Transverse Wave* the particle displacement is perpendicular to the direction of wave propagation

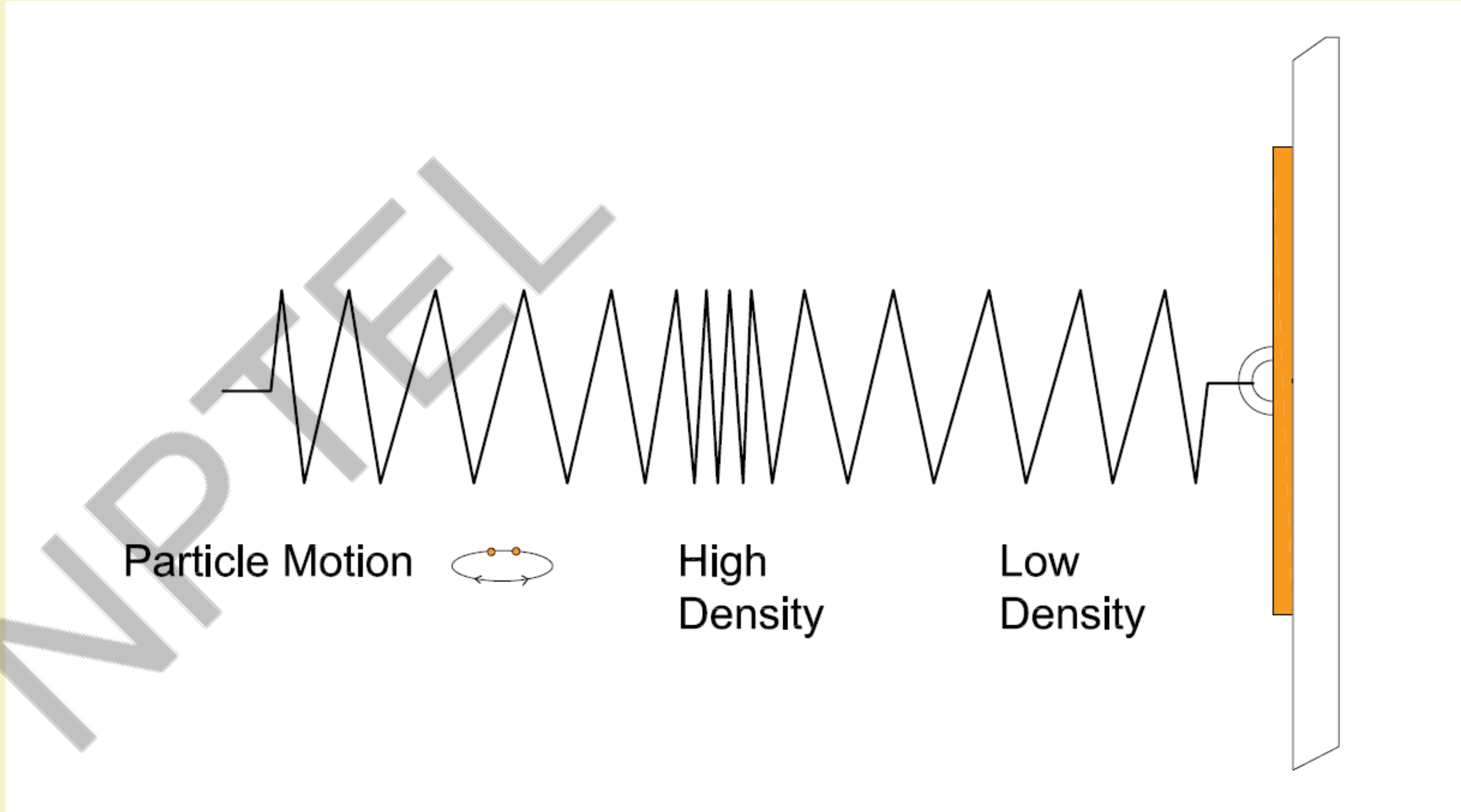
Transverse Wave

Longitudinal Wave Motion

Direction of Wave

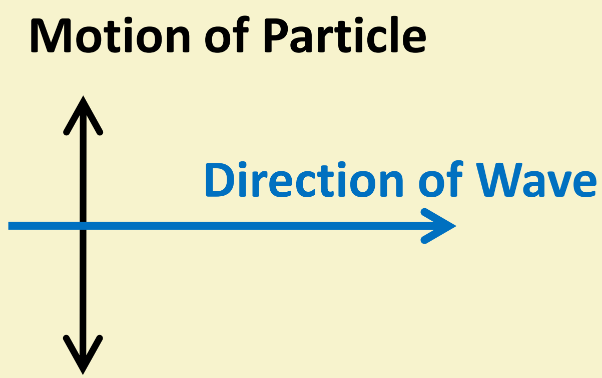


Motion of Particle

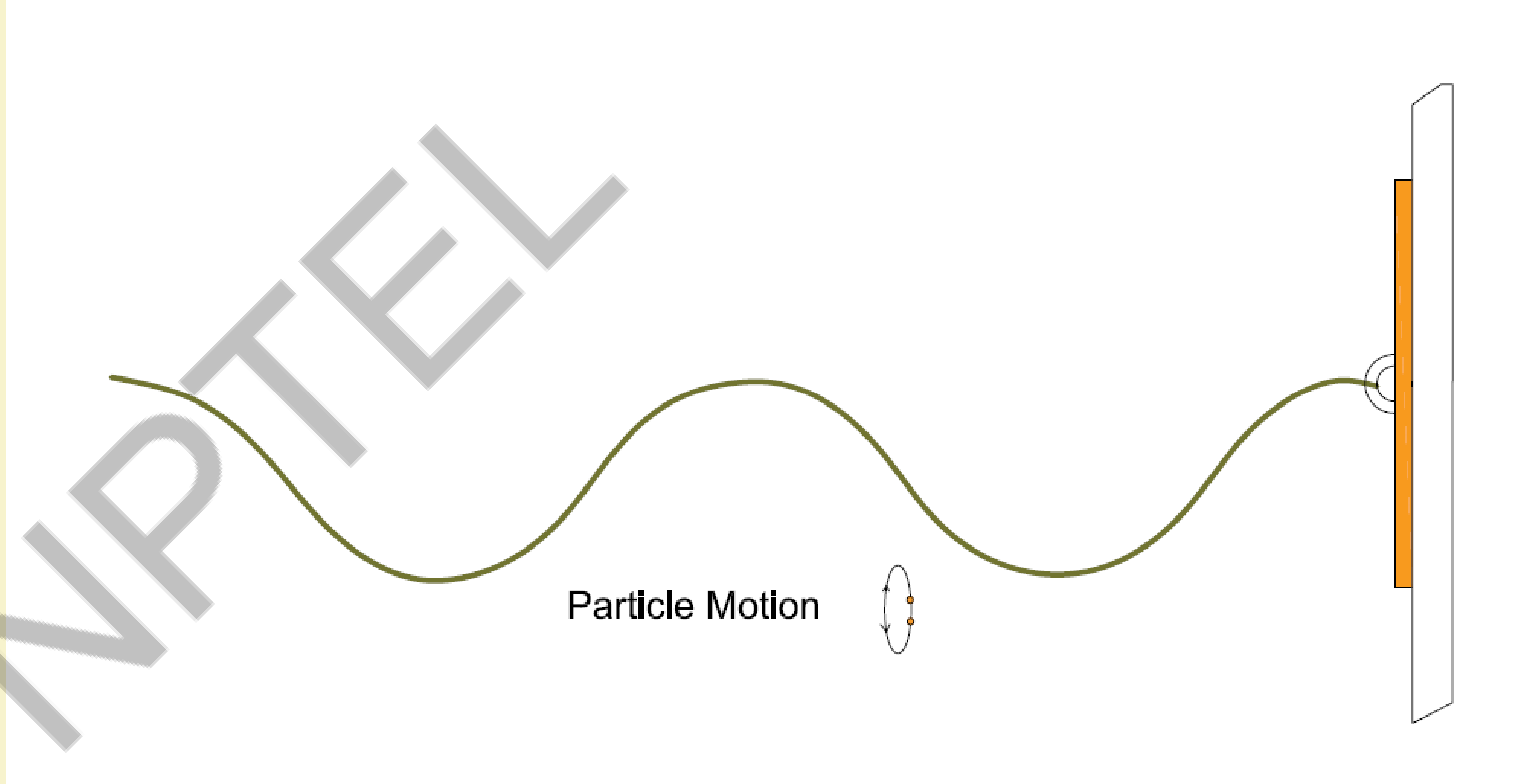


- **Motion of a Spring**
- **Sound Wave**
- **P-Wave**

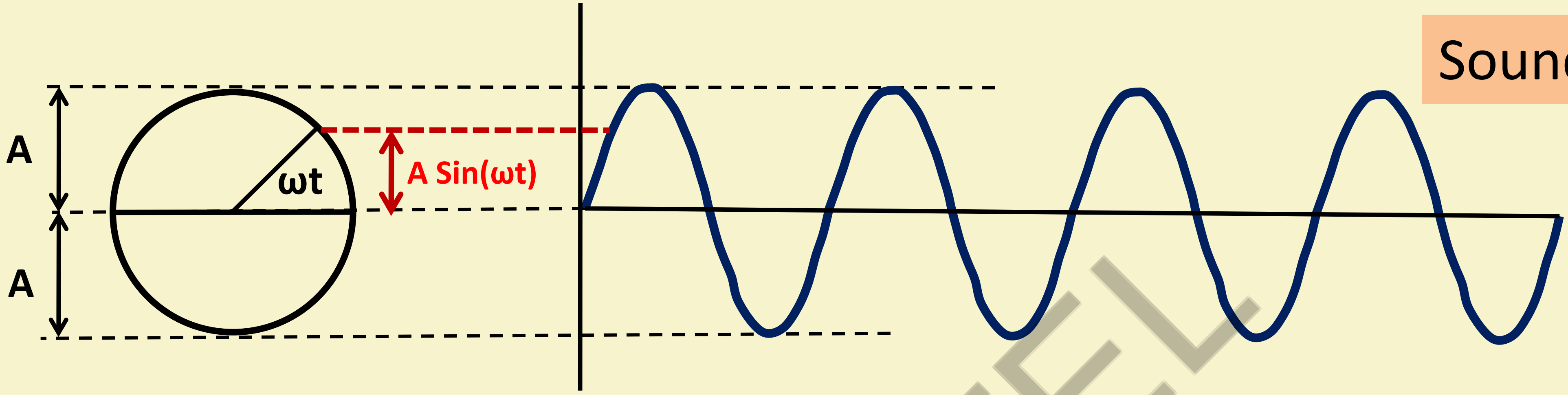
Transverse Wave Motion



- **Motion of a String**
- **Water Ripples**
- **S-Wave**
- **Electromagnetic Wave**



Sound Wave Equation



$$y = A\sin\varpi t$$

Time period is the time taken for a complete revolution (2 π radians) with angular velocity ω

T = Time period = (2π/ω)

$$y = A\sin\left(\frac{2\pi}{T}\right)t$$

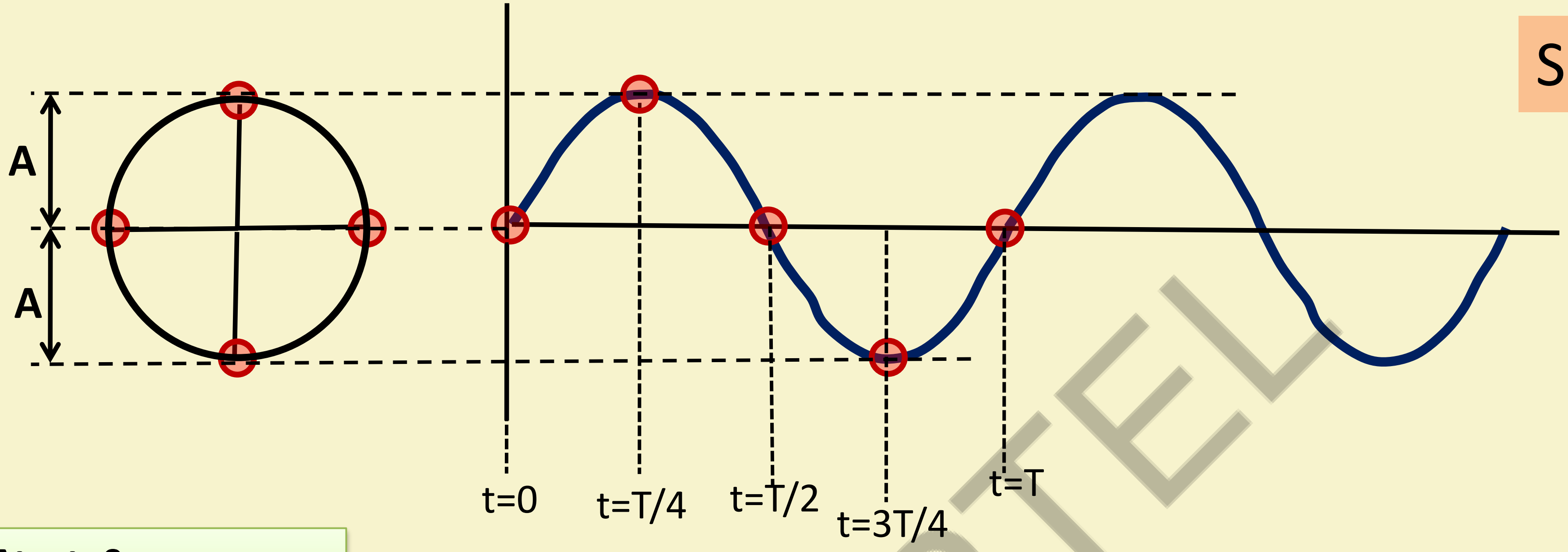
A= Amplitude

ω = Circular frequency (rad/sec)

t = time

ω t = angular movement after time ‘t’

Sound Wave Equation



At t=0
y=0

At t= T/4
y= A sin (2π/T) (T/4) = A Sin(π/2) = A

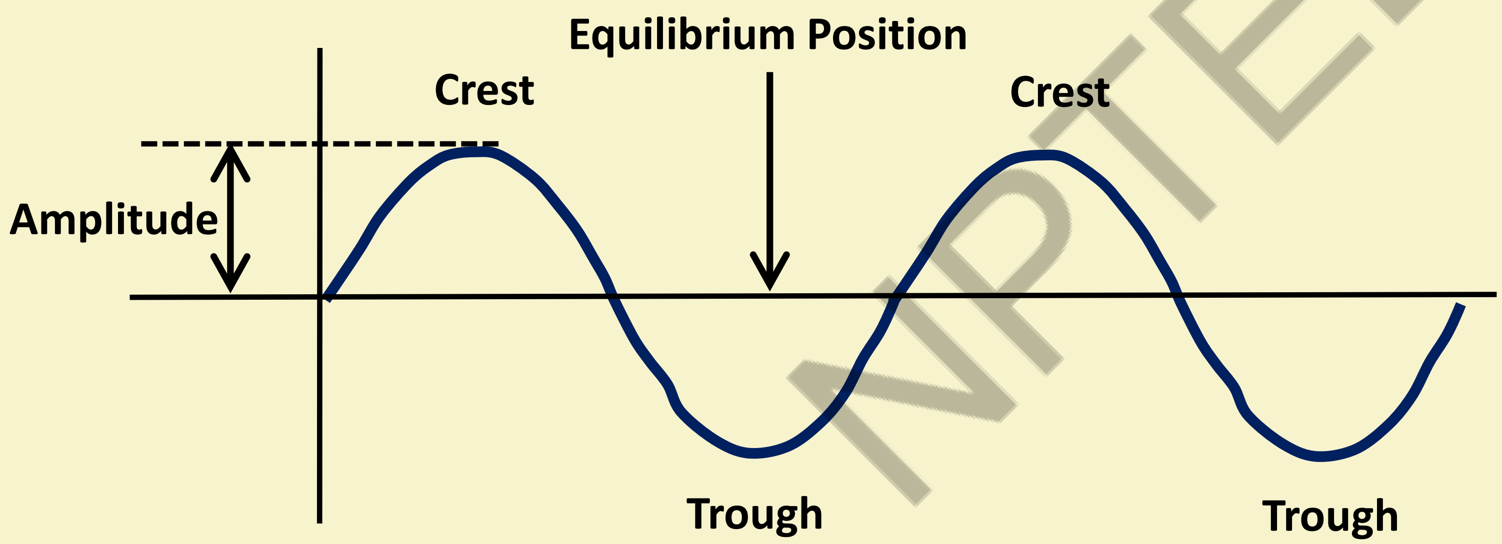
At t= 3T/4
y= A sin (2π/T) (3T/4) = A Sin(3π/2) = -A

At t= T/2
y= A sin (2π/T) (T/2) = A Sin(π) = 0

At t= T
y= A sin (2π/T) (T) = A Sin(π) = 0

Amplitude

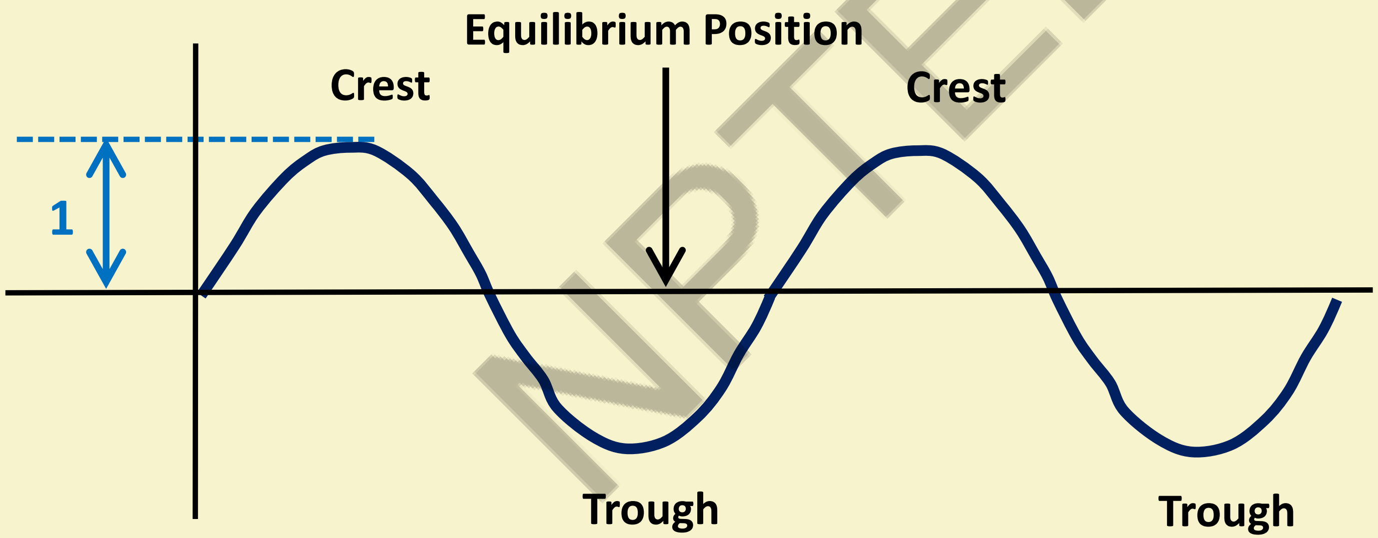
The maximum extent of a vibration or oscillation in a propagating wave motion, measured from the position of equilibrium is called **Amplitude**



- **Amplitude**
  - Peak- Amplitude
  - Peak-to-Peak Amplitude
  - Root-mean-Square Amplitude

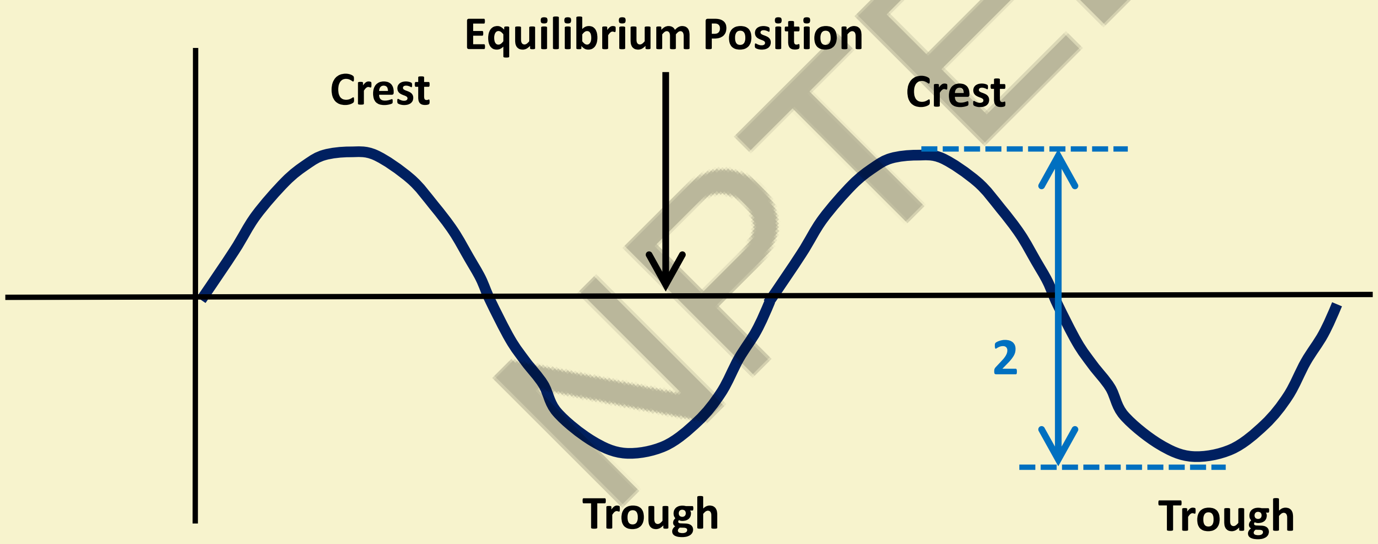
Peak- Amplitude

The extent of a vibration between the <u>Crest to the position of equilibrium</u> in a propagating wave motion is called Peak- Amplitude [1]



Peak-to-Peak Amplitude

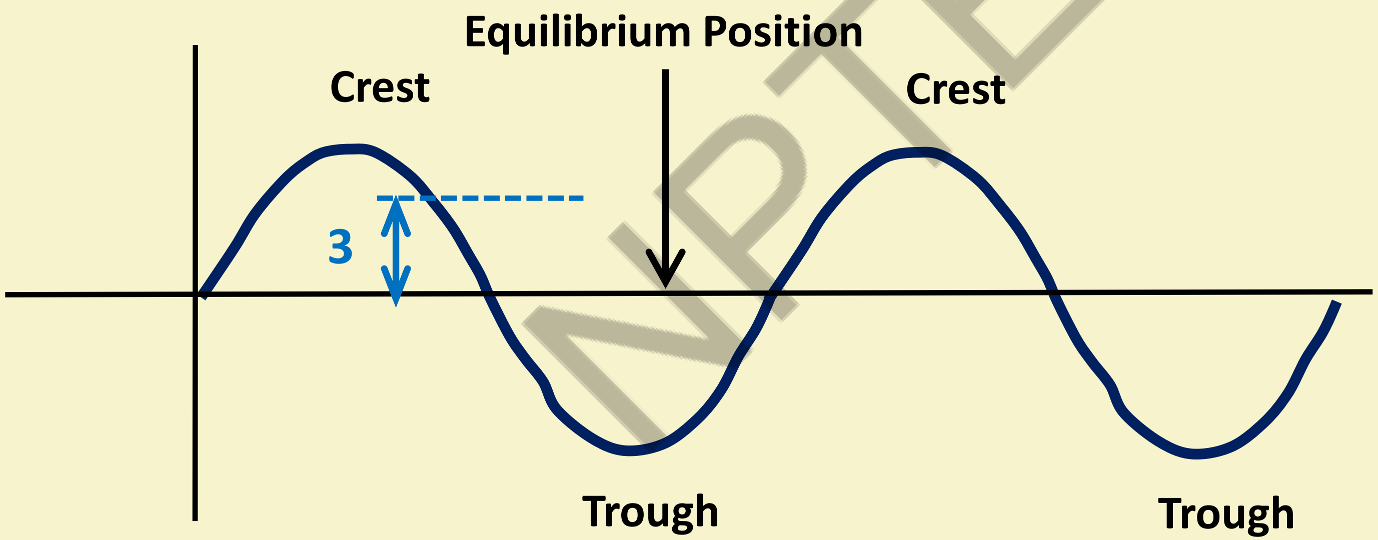
The extent of a vibration between the Crest to Trough in a propagating wave motion is called Peak-to-Peak Amplitude [2]



Root-mean-Square Amplitude

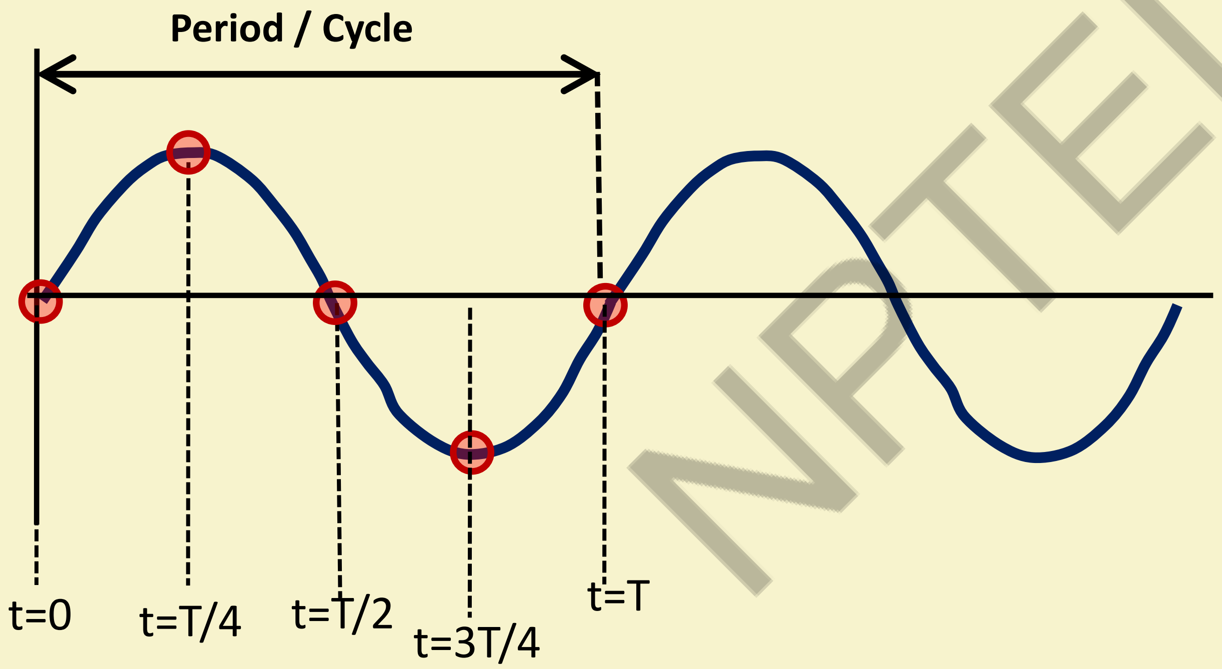
The square root of the squared average values of the waveform is called Root-mean-Square Amplitude [3]

In the case of the sine wave, the RMS value is 0.707 times the peak value



Time Period

The time needed for one complete cycle of vibration to pass a given point is called **Time Period**.

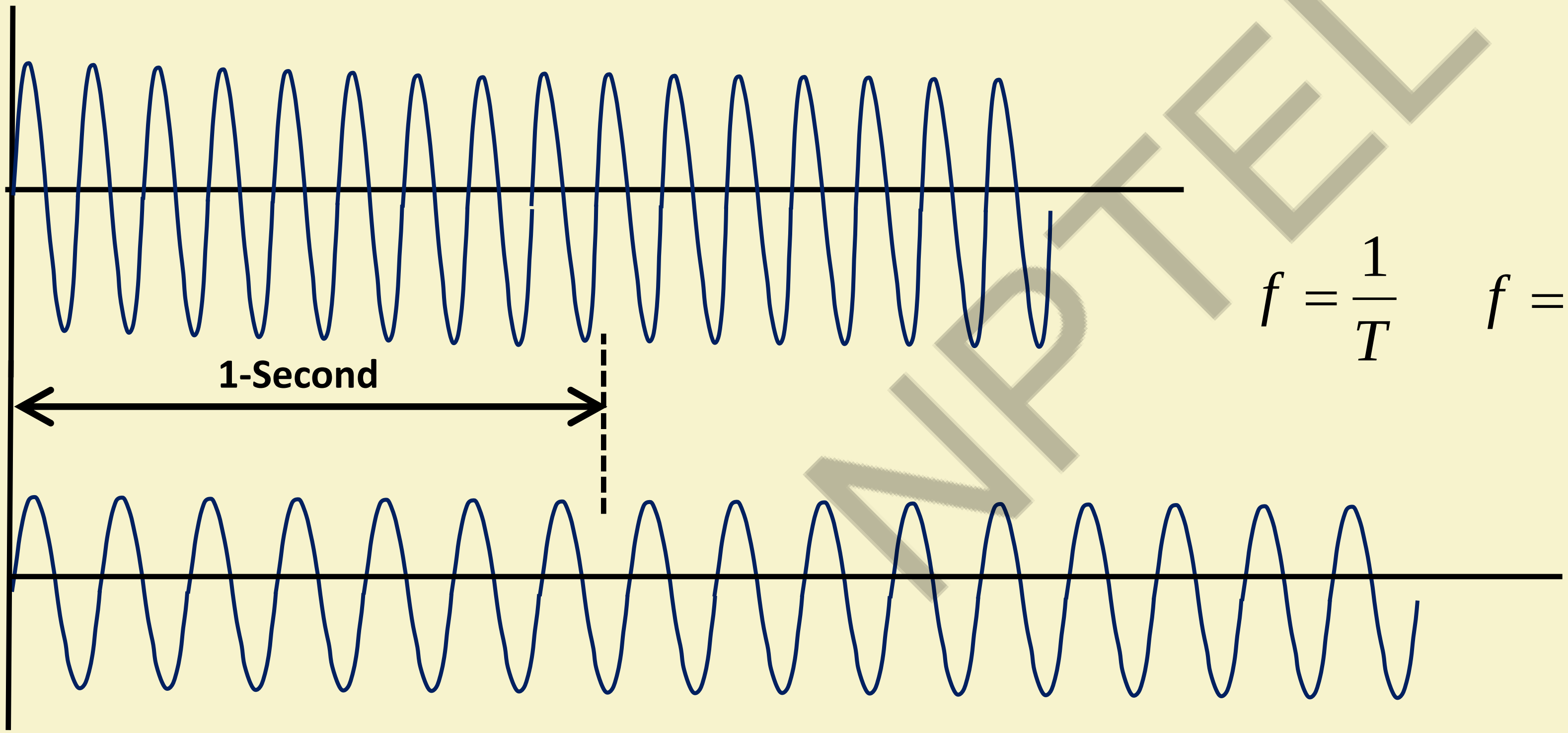


$$T = \frac{2\pi}{\omega} \qquad T = \frac{1}{f}$$

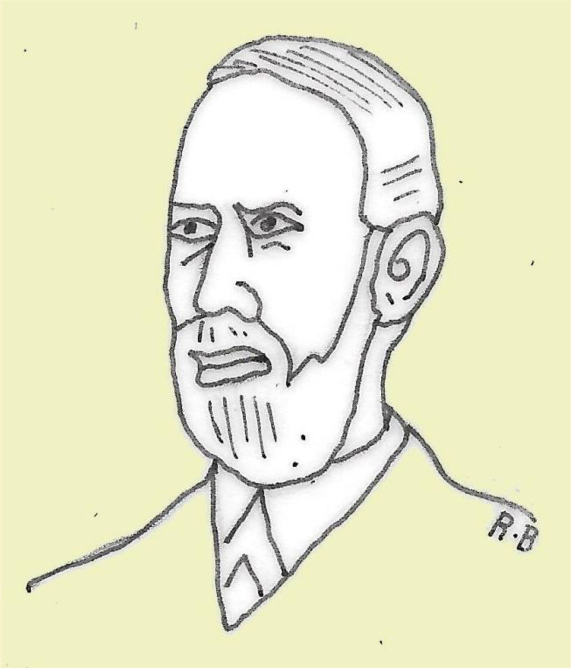
Frequency

Frequency describes the number of complete wave cycle that pass a fixed point in unit time.

Usually frequency is measured in cycles per second (CPS) or hertz unit, named in honor of the 19th-century German physicist Heinrich Rudolf Hertz

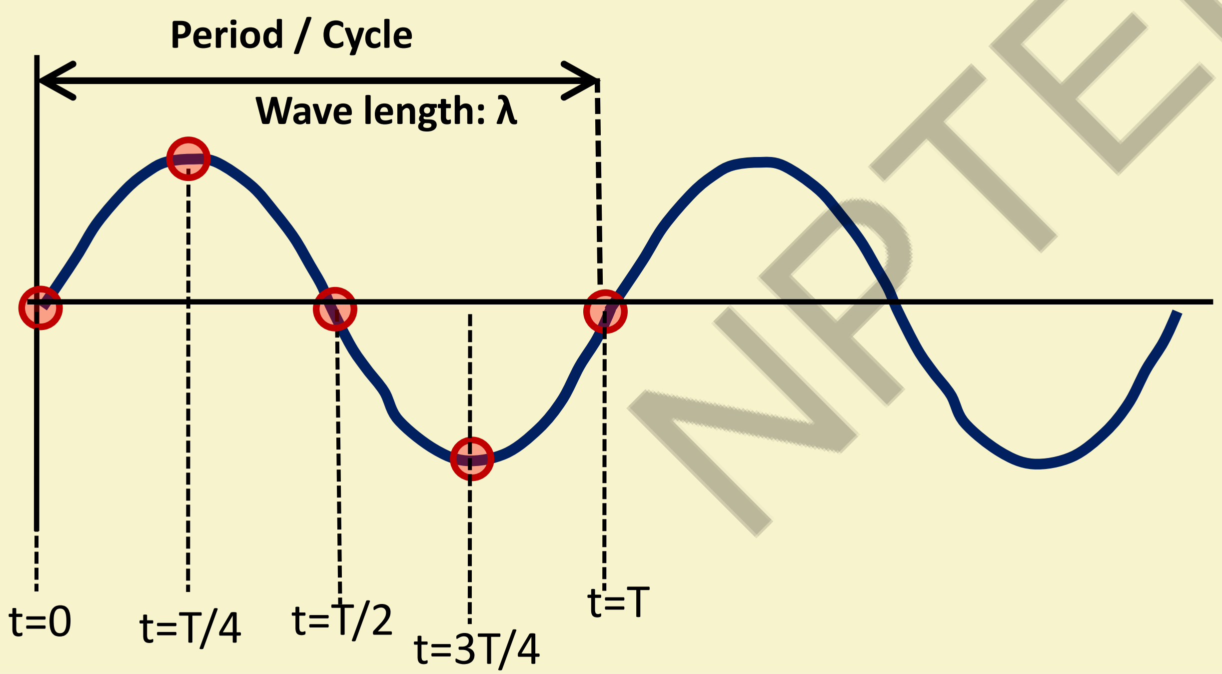


$$f = \frac{1}{T} \qquad f = \frac{\omega}{2\pi}$$



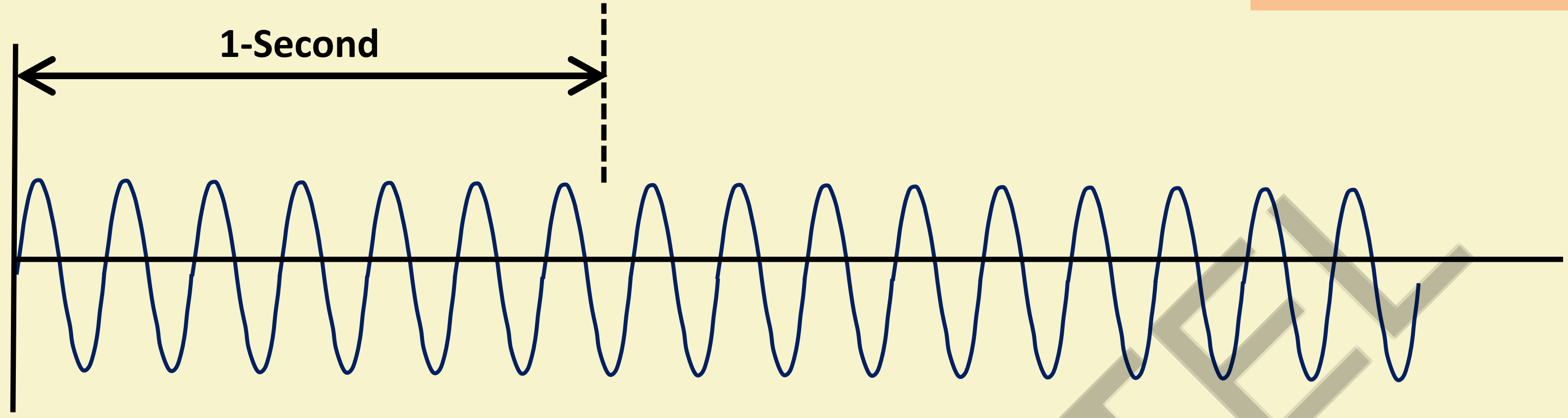
Wavelength

The distance between two successive crests or troughs, or the distance of a complete cycle of a wave propagation of in the direction of wave motion is called **Wavelength**.



Sound Wave: Frequency & Wave Length

Distance = Frequency times Wave Length



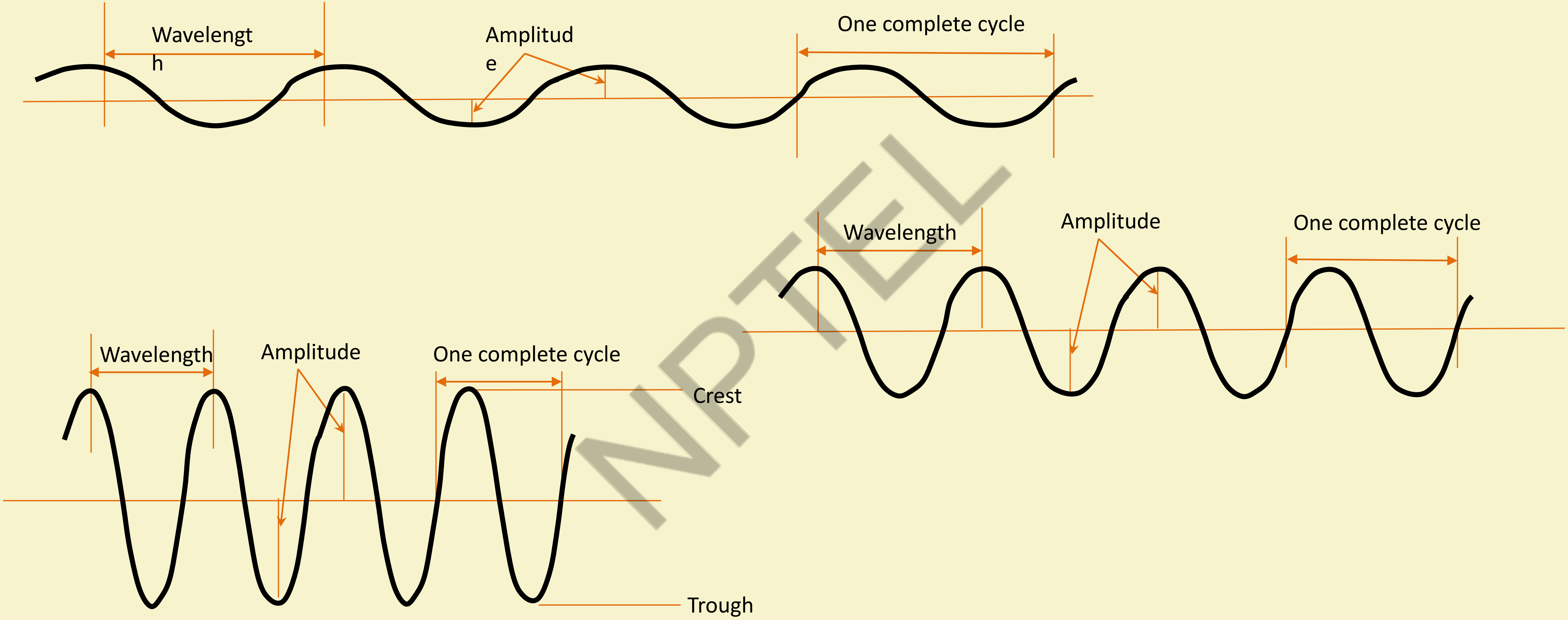
v = Velocity of Propagation

v = No. of Cycle per second X length of each Cycle

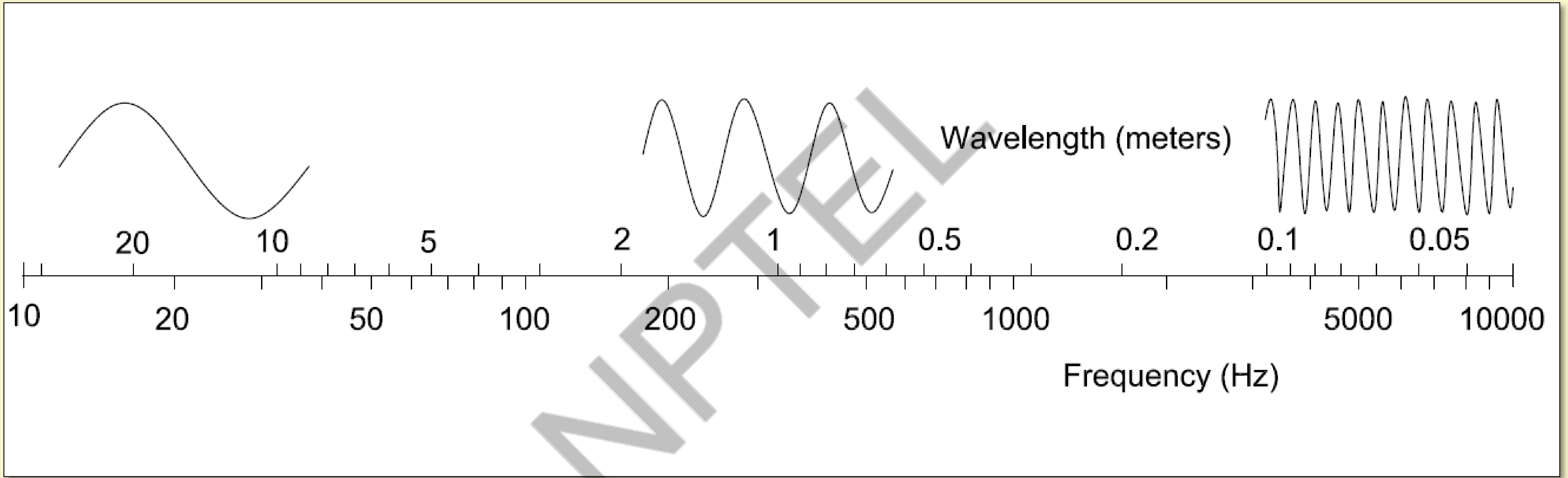
v= Frequency (**n**) X Wave-Length (**λ**)

$$\mathbf{v = n \,.\, \lambda}$$

Variation of Frequency, Amplitude & Wavelength

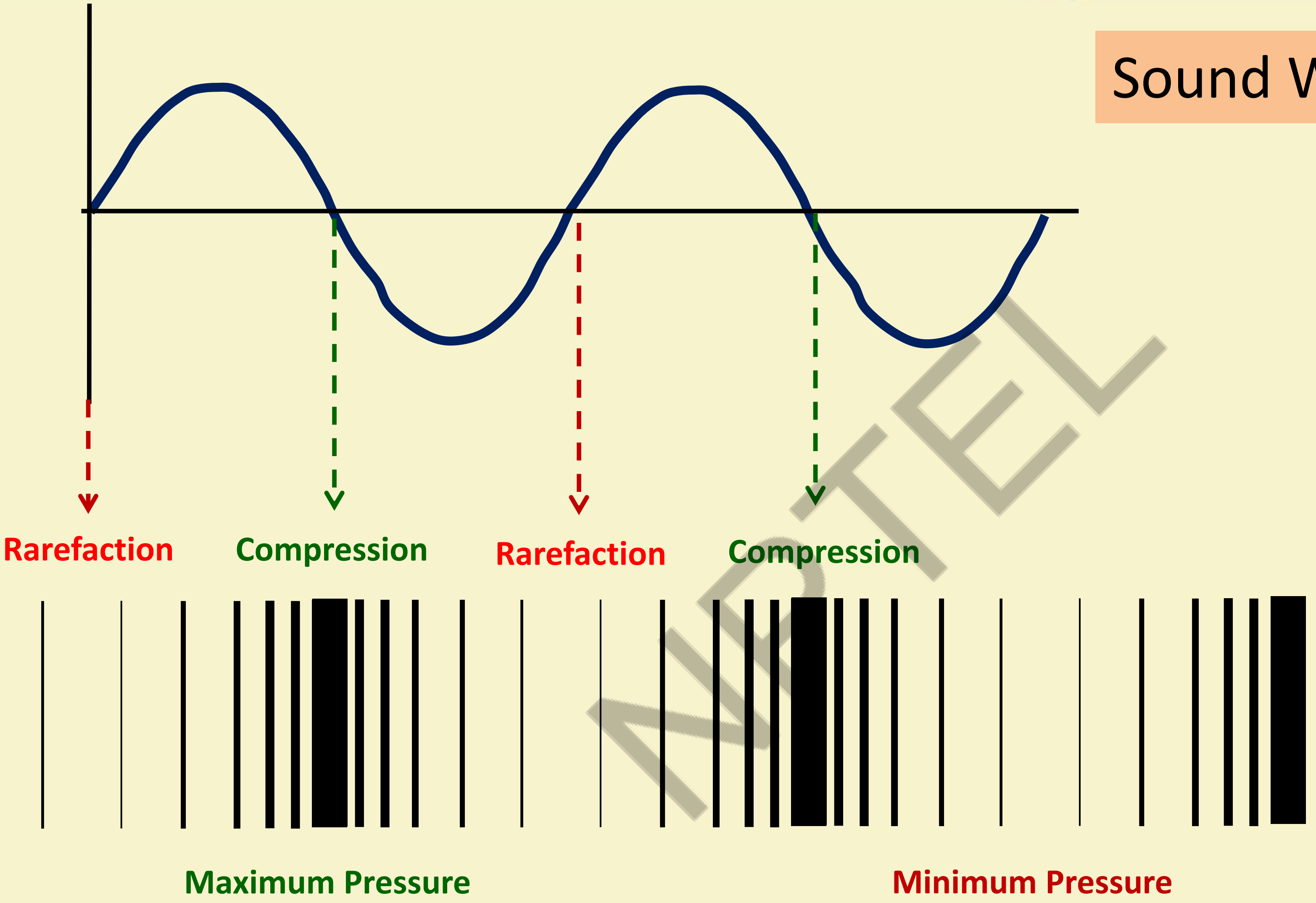


Nomogram of Frequency & Wave Length

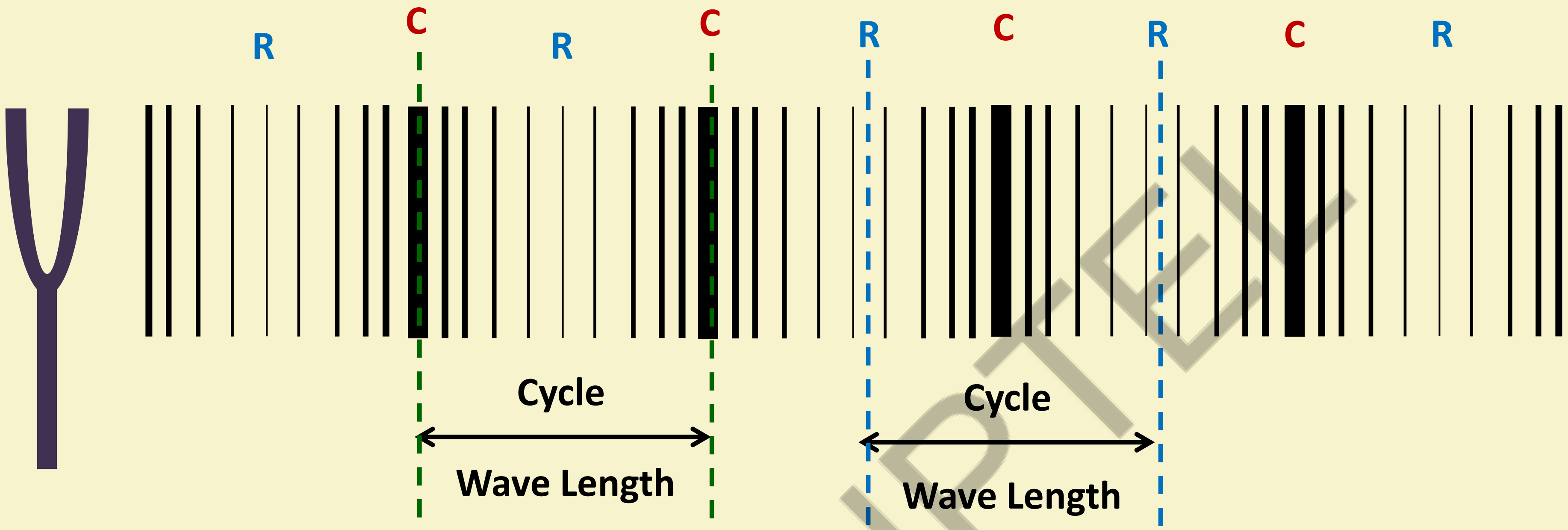


Nomogram of Frequency and Wave Length

Sound Wave Propagation in Air



Sound Wave Propagation in Air



Velocity of Sound in Air (c) is depend upon:

- Atmospheric Pressure (p)
- Density of Air (ρ)
- Temperature of Air (t_a)

$$c = 331\sqrt{\left(1 + \frac{t_a}{273}\right)}$$

$$c = \sqrt{\frac{1.4p}{\rho}}$$

$$c = 331 + 0.6 \times t_a$$

The speed of sound in air at room temperature is 340 m/s

Home Work

Can you find the **Amplitude and Frequency** of a wave if its equation is given?

Try with: $y = 2X10^{-3}\,Sin(600t)$

Can you find the **Wavelength** also, in normal room temperature air?

Suppose, **two different sound wave** having **same amplitude**.
The **frequency** of one wave is **double of the other**.

Can you **sketch** the one full cycle of both the wave motions

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3. **Mechanical and Electrical Equipment for Buildings**, Walter T. Grondzik, Alison G. Kwok, Benjamin Stein and John S. Reynolds, John Wiley & Sons, Inc. (11th Edition) [Part-IV]

End of Lecture 02: Introduction to Architectural Physics

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Architectural Acoustics

Lecture 03: Frequency and Octave

Dr. Shankha Pratim Bhattacharya

Department of Architecture & Regional Planning

Learning Objective

- Distinguish between various combination of sound frequencies
- Interpret the super imposition of wave motion

Frequency

- The number of oscillation or cycle or displacement per unit time is known as frequency
- So frequency is numerically equal to **Cycles per Second (CPS).** The unit of frequency is **Hertz (Hz)**
- A normal human ear responds to sounds within the audio frequency range about **20 to 20000 Hz**

Frequency & Tone

Tone Sound Sensation

Pure Tone Sound Sensation consists of <u>a Single Frequency</u>

Striking a tuning fork
Vibration of string of a guitar

Complex Tone Sound Sensations consists of <u>more than one frequency</u>

Speech,
Music,
Road side noise

Harmonics

Rest all higher frequencies — **Overtones or Integral Frequencies or Partials**

Complex Tone 50 75 80 100 160 250 325 450 535 750

Fundamental Tone — The lowest frequency present in the complex tone

50 75 80 **100** 160 **250** 325 **450** 535 **750**

Harmonics — Numerical integer multiples of the fundamental (including the fundamental)

Octave

25 50 75 100 150 200 350 400 500 800 950

Harmonics

25 50 75 100 150 200 350 400 500 800 950

Octave If a frequency is double of the another, then these two are called Octave

Octave Band Central Frequency

31.5	63	125	250	500	1000	2000	4000	8000	16000
15	18	21	24	27	30	33	36	39	42

Band width

OBCF: f — 31.5

- f-0.3xf=0.7f — **0.7 x 31.5 = 22**
- f+0.4xf=1.4f — **1.4 x 31.5 = 44**

OBCF: 2f — 63

- 2f-0.3x2f=1.4f — **0.7 x 63 = 44**
- 2f+0.4x2f=2.8f — **1.4 x 63 = 88**

Band No = (10log f)

10 log(31.5) = 15
10 log(63.0) = 18

Octave Band Central Frequency

OBCF(f)	Band No.(10log f)	Band width
		22
31.5	15	
		44
63	18	
		88
125	21	
		175
250	24	
		350
500	27	
		700

OBCF(f)	Band No.(10log f)	Band width
		700
1000	30	
		1400
2000	33	
		2800
4000	36	
		5600
8000	39	
		11200
16000	42	
		22400

Necessity of Octave Band

Octave criteria gives an opportunity to logically select some specific frequencies out of many

The logarithm of octave frequencies are separated by equal distance

The octave band central frequencies provide the common platform for material testing and assess the acoustical data

One Third Octave Band

1/1 Octave Band	Band No		1/3 Octave Band
	14	→ Antilog 1.4 →	25
31.5	10 log(31.5) = 15		31.5
	16	→ Antilog 1.6 →	40
	17	→ Antilog 1.7 →	50
63	10 log(63.0) = 18		63
	19	→ Antilog 1.9 →	80

One Third Octave Band

25

(31.5/25) = 1.26

31.5

(40/31.5) = 1.26

40

(50/40) = 1.25

50

(63/50) = 1.26

63

(80/63) = 1.26

80

1/1 Octave Band

(63/31.5) = 2

1/3 Octave Band

$$\sqrt[3]{2} = 1.2599$$

In One-third Octave band, the next higher frequency is 'Cube root of Two' times the Immediate lower frequency

One Third Octave Band

Octave	Band No.			1/3rd Octave
		14	Antilog 1.4	**25**
31.5	10log 31.5	15		
		16	Antilog 1.6	**40**
		17	Antilog 1.7	**50**
63	10log 63	18		
		19	Antilog 1.9	**80**
		20	Antilog 2.0	**100**
125	10log 125	21		
		22	Antilog 2.2	**160**
		23	Antilog 2.3	**200**
250	10log 250	24		
		25	Antilog 2.5	**315**
		26	Antilog 2.4	**400**
500	10log 500	27		
		28	Antilog 2.8	**630**
		29	Antilog 2.9	**800**

One Third Octave Band

Octave	Band No.			1/3rd Octave
		31	Antilog 3.1	1260
		32	Antilog 3.2	1600
2000	10log 2000	33		
		34	Antilog 3.4	2500
		35	Antilog 3.5	3150
4000	10log 4000	36		
		37	Antilog 3.7	5000
		38	Antilog 3.8	6300
8000	10log 8000	39		
		40	Antilog 4.0	10000
		41	Antilog 4.1	12500
16000	10log 16000	42		
		43	Antilog 4.3	20000

THIRTY One-third Octave Band Central Frequencies

1/1 OBCG & 1/3 OBCF

25 **31.5** 40 50 **63** 80 100 **125** 160 200 **250**

315 400 **500** 630 800 **1000** 1260 1600 **2000**

2500 3150 **4000** 5000 6300 **8000** 10000 12500 **16000** 20000

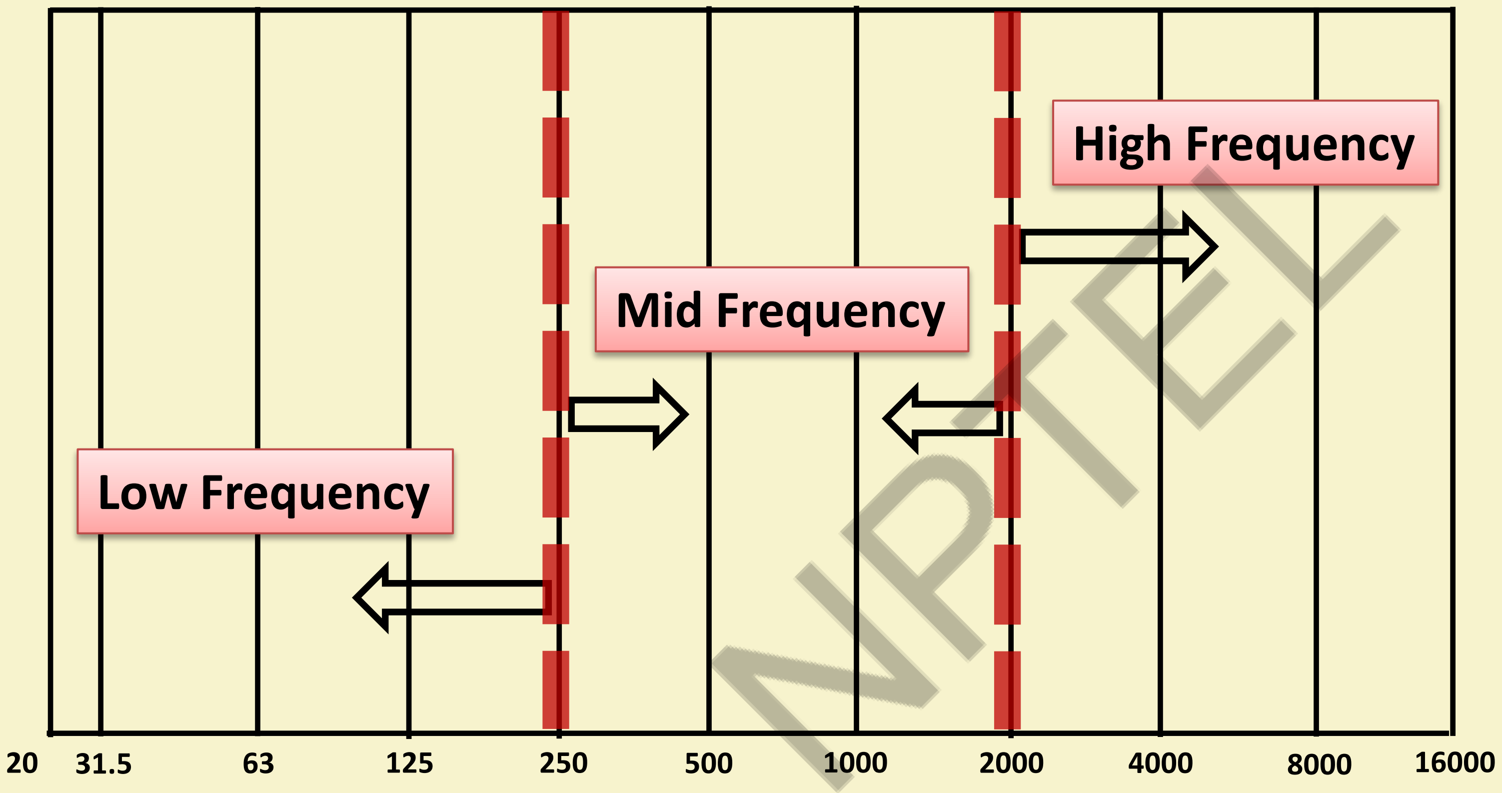
TEN Octave Band Central Frequencies

31.5 **63** **125** **250**

500 **1000** **2000**

4000 **8000** **16000**

Low, Medium and High Frequency Sound



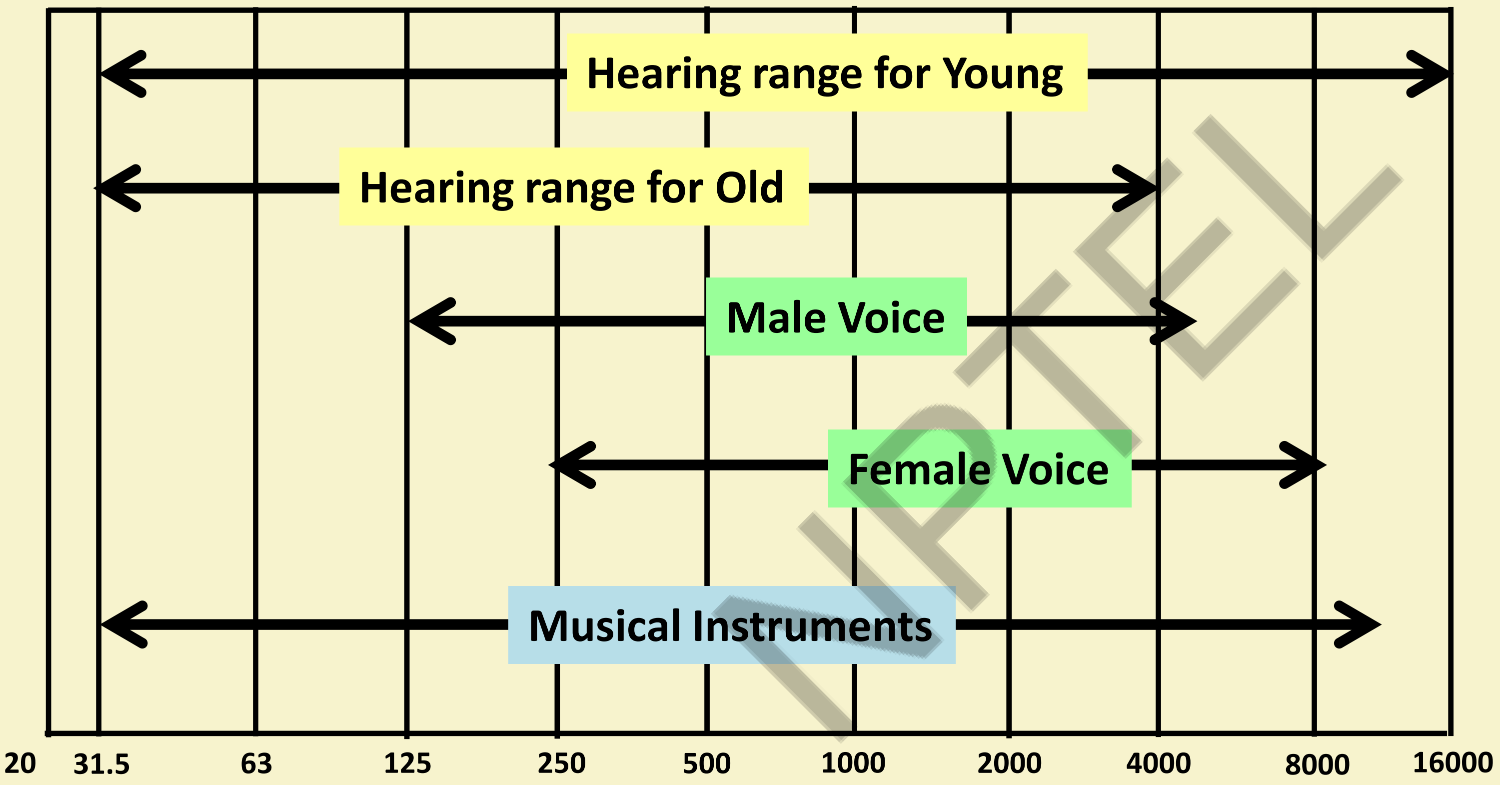
Humans can listen to it **20Hz to 20,000Hz**.
This audio spectrum is divided mainly into 3 categories.

Bass is low frequency range, approximately 20Hz to 250Hz.

Mid range is approximately 250Hz to 2000Hz.

Treble is the high frequency range, above 2000Hz.

Frequency Range of Audible Sound



Home Work

Can you distinguish the **Harmonics and Octave** from a given set of complex tone?

Try with the complex tone given:

23 36 46 51 69 85 92 154 161 184 236 368 483

Suppose, **two different sound wave** having the following data

Sound wave 1: Amplitude = 50mm & Frequency = 79.577 Hz

Sound wave 2: Amplitude = 2.5mm & Frequency = 318.31 Hz

Can you find the **particle displacement** of the superimposed wave at **Time = 0.25 sec**

Bibliography

1. **Acoustics in the Built Environment**, Duncan Templeton, Architectural Press; 2nd Edition
2. **Architectural Acoustics**, K.B.Genn, Burel & Kjaer, 2nd Edition
3. **Mechanical and Electrical Equipment for Buildings**, Walter T. Grondzik, Alison G. Kwok, Benjamin Stein and John S. Reynolds, John Wiley & Sons, Inc. (11th Edition) [Part-IV]

End of Lecture 03: Frequency and Octave

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Architectural Acoustics

Lecture 04: Sound Pressure and Intensity Level

Dr. Shankha Pratim Bhattacharya

Department of Architecture & Regional Planning

Learning Objective

Convert the Sound Intensity and Pressure into Sound Level

Calculate the Resultant Sound Level from multiple Sound source

Logarithmic Operations

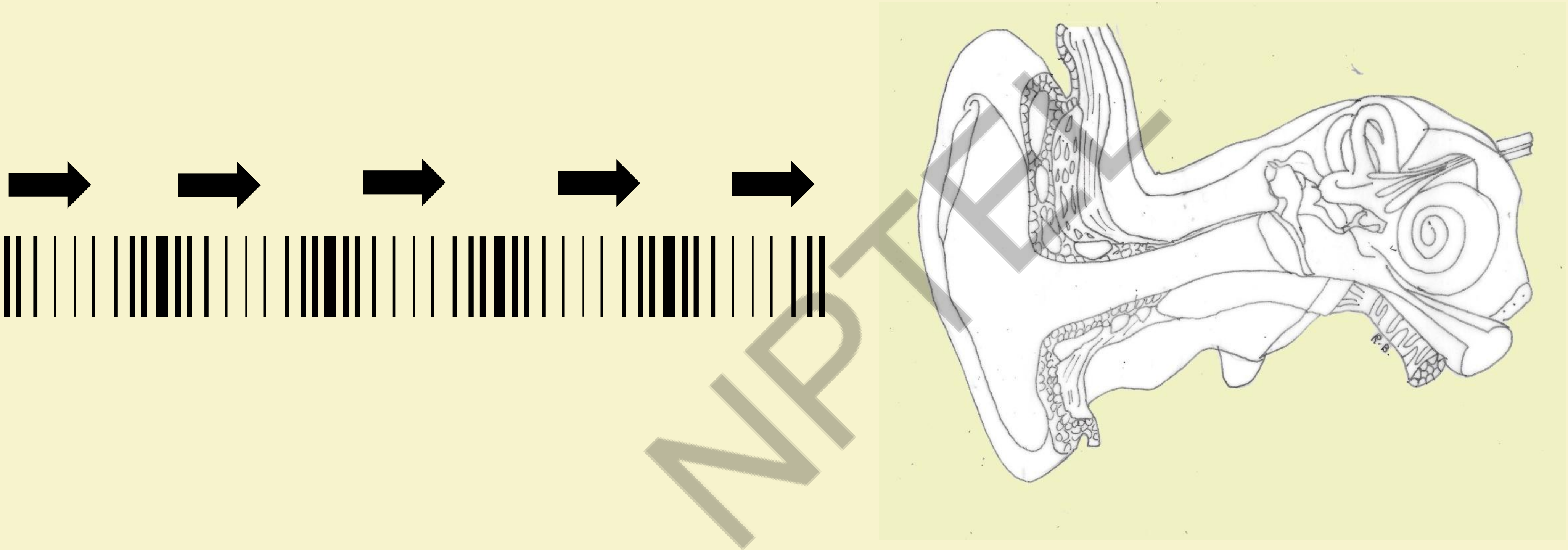
$$\log a = x, \Rightarrow 10^{x} = a$$

$$(\log a) + (\log b) = \log(ab)$$

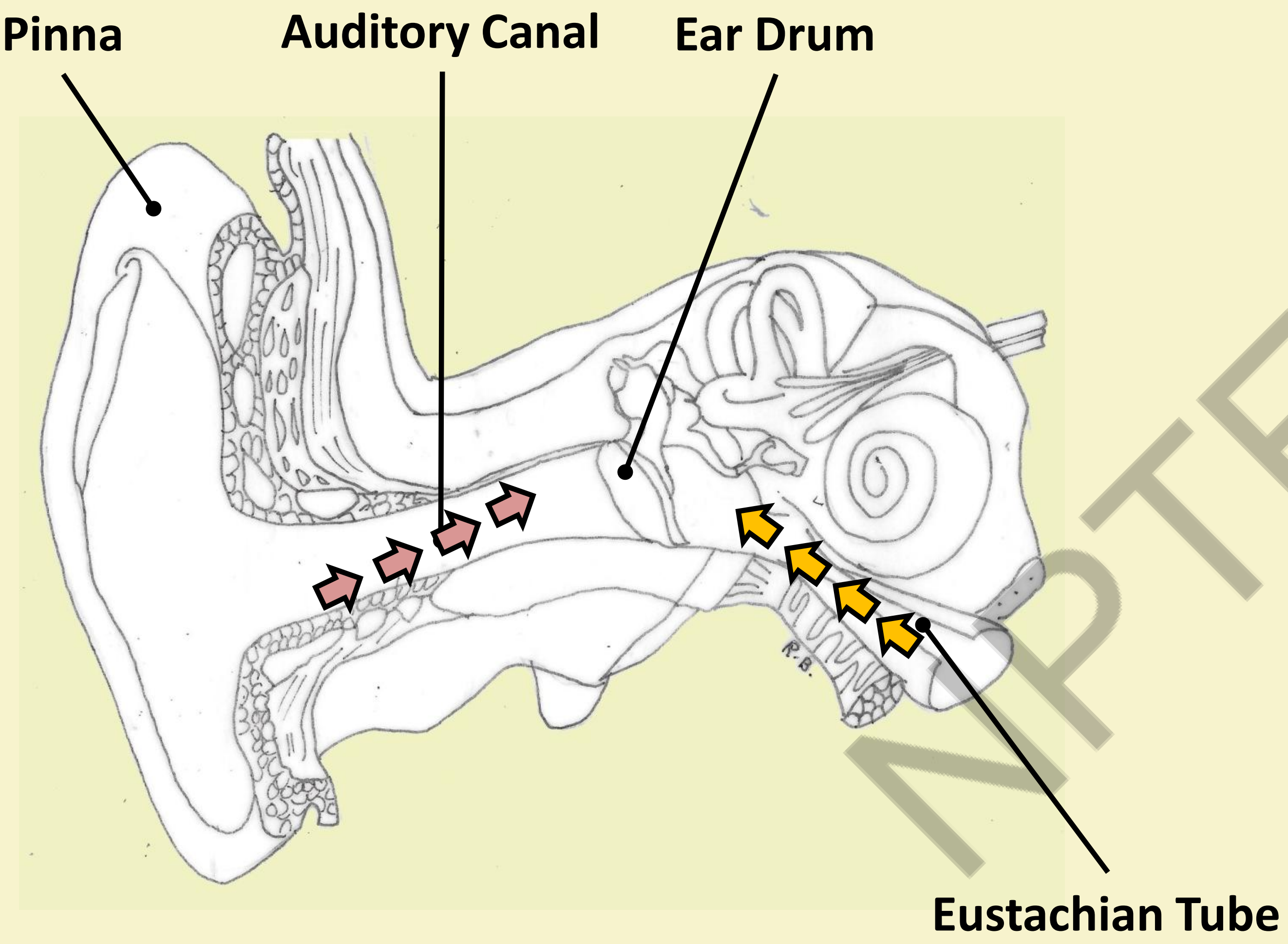
$$(\log a) - (\log b) = \log\left(\frac{a}{b}\right)$$

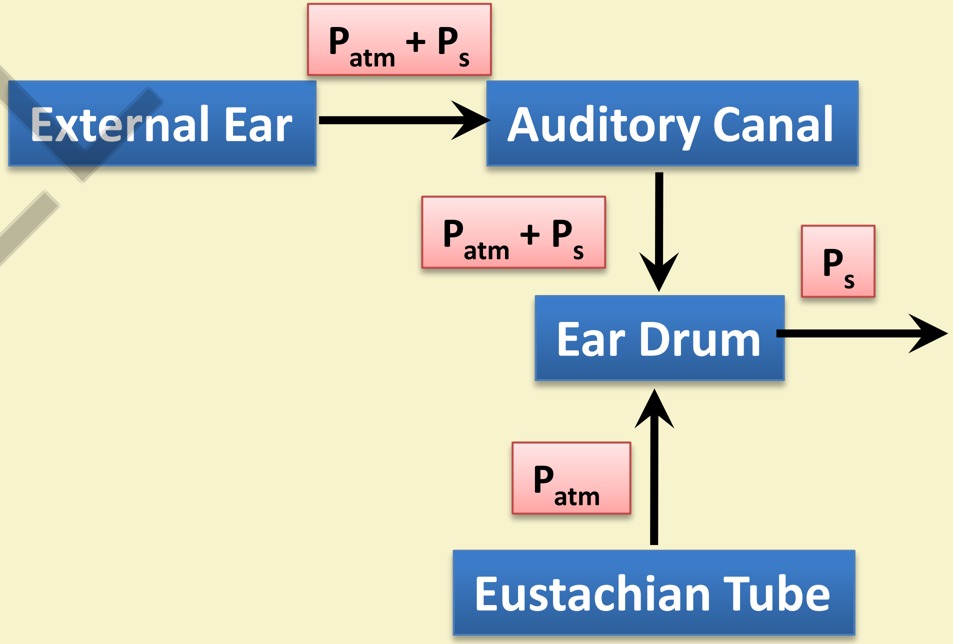
$$\log a^{n} = n \times \log a$$

Human Hearing



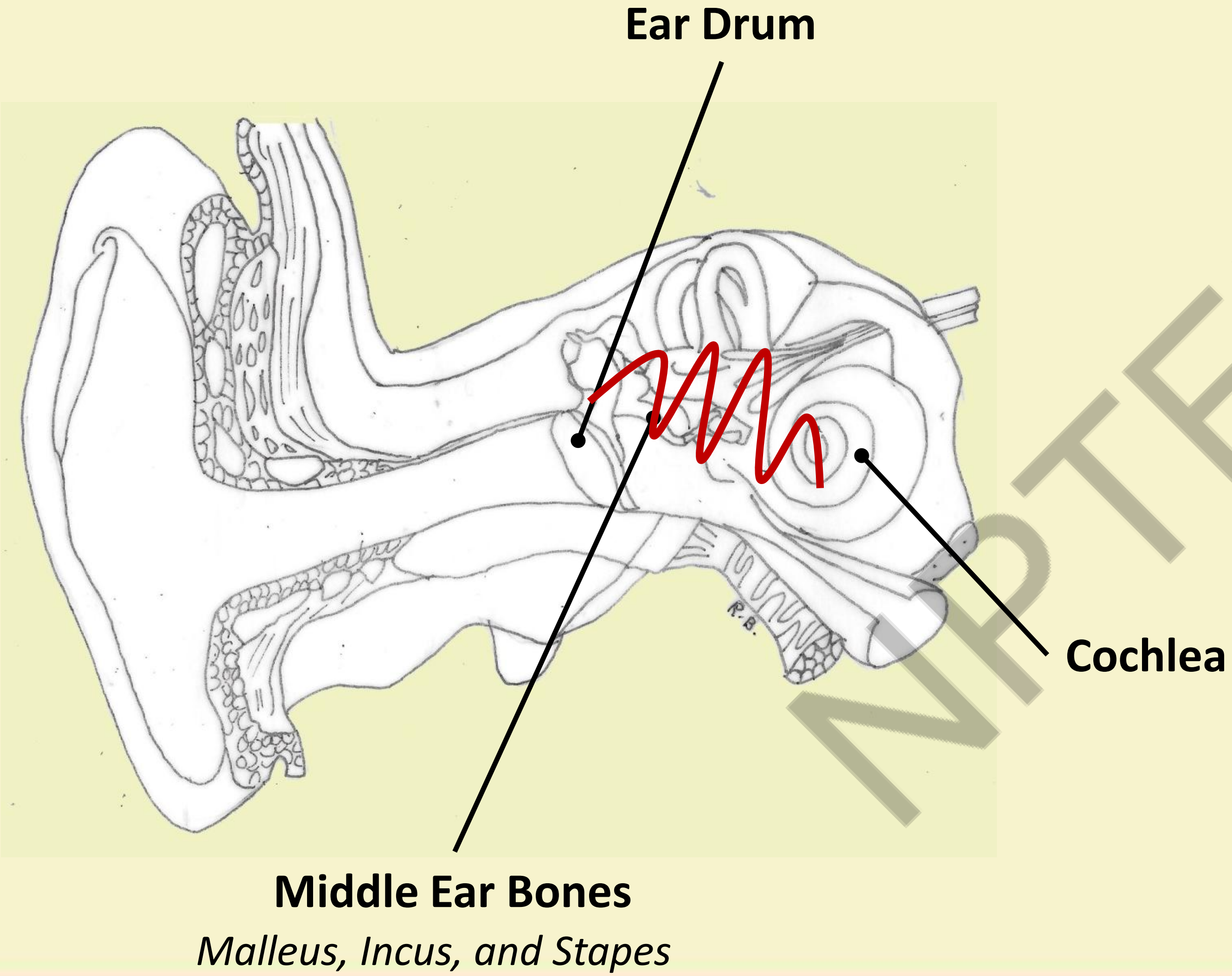
Human Hearing

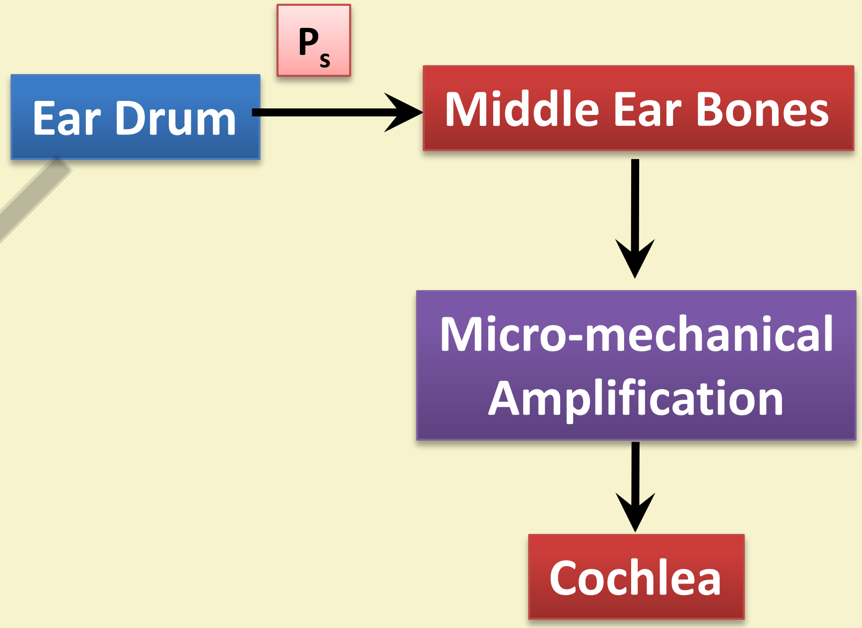




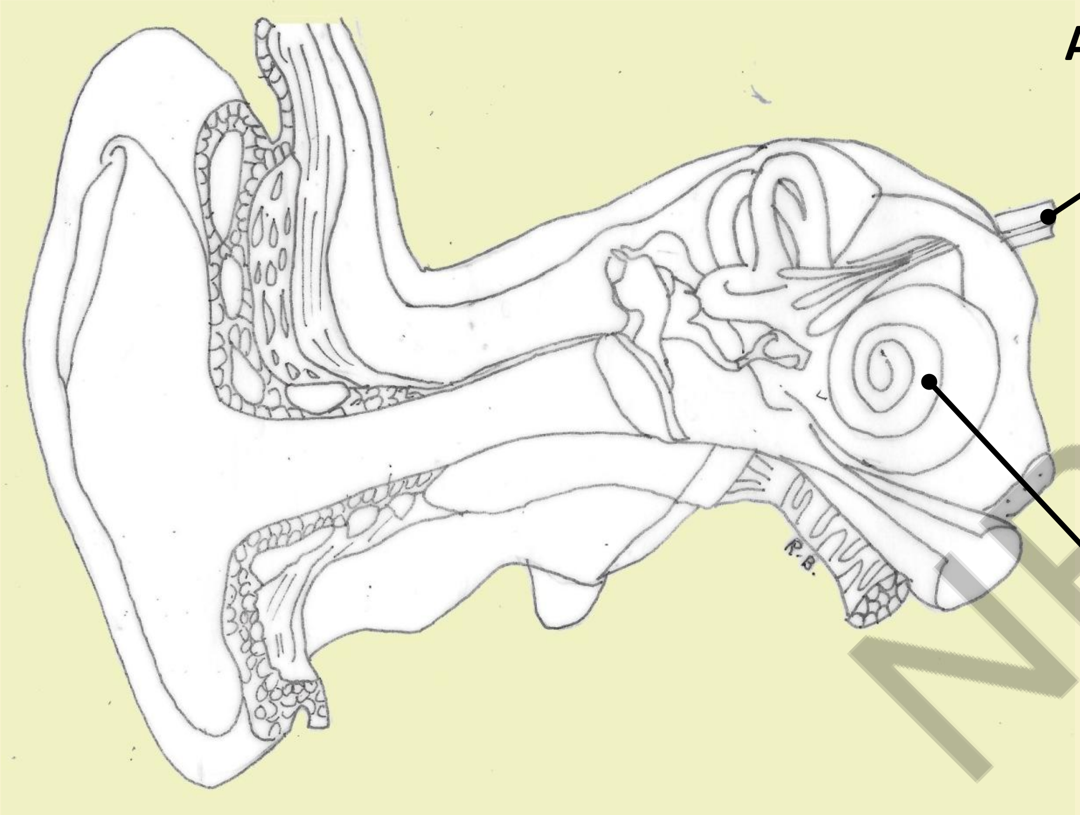
Atmospheric Pressure: $\mathbf{P_{atm}}$
Pressure due to Sound: $\mathbf{P_s}$

Human Hearing





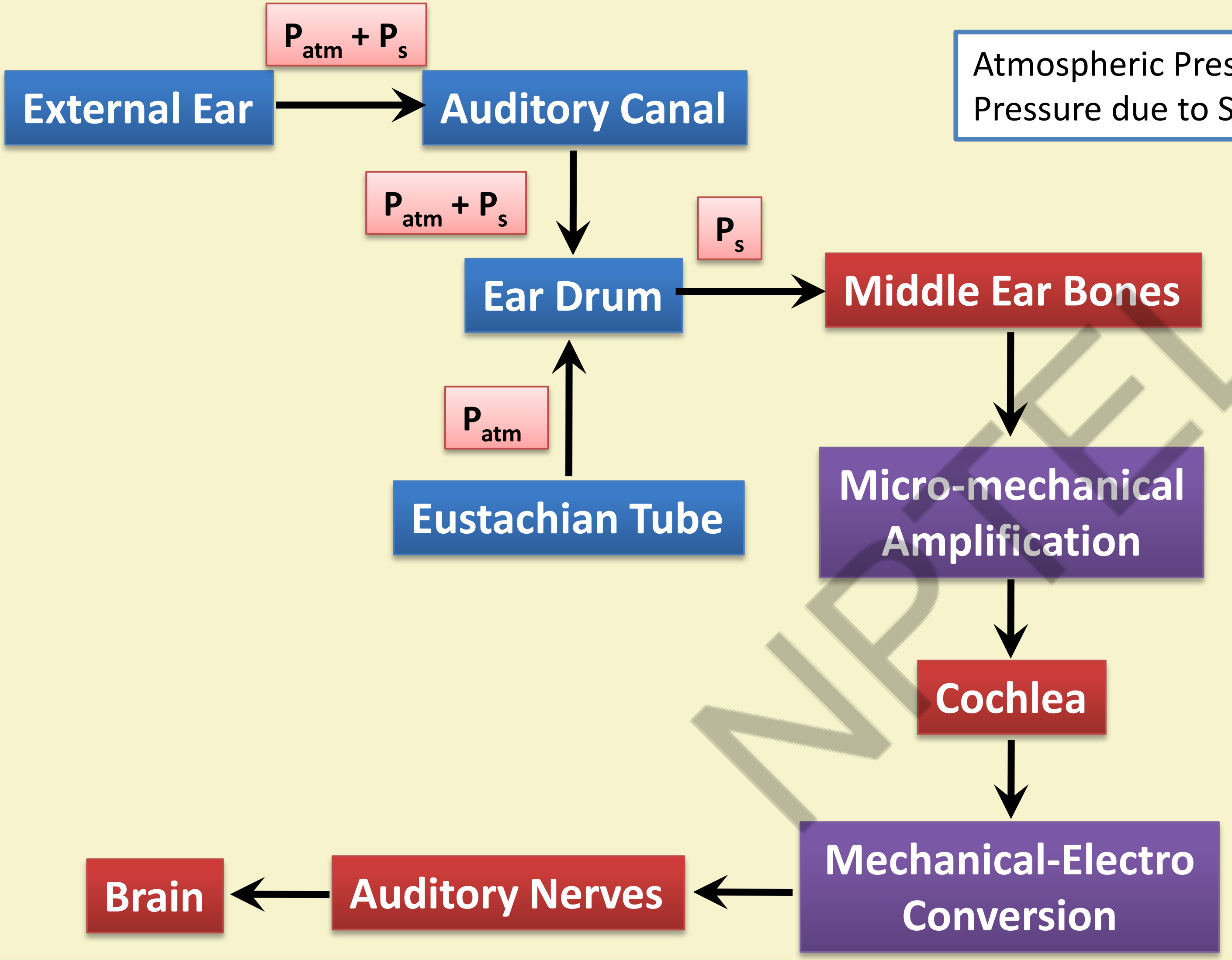
Human Hearing



Cochlea → Mechanical-Electro Conversion → Auditory Nerves → Brain

Human Hearing

Atmospheric Pressure: $\mathbf{P_{atm}}$
Pressure due to Sound: $\mathbf{P_s}$



Psychologist Weber suggested:-

Change of **Subjective Response (R)**
is proportional to
the Functional **change of Stimulus (S)**

$$\delta R = \frac{\delta S}{S}$$

Integrating:

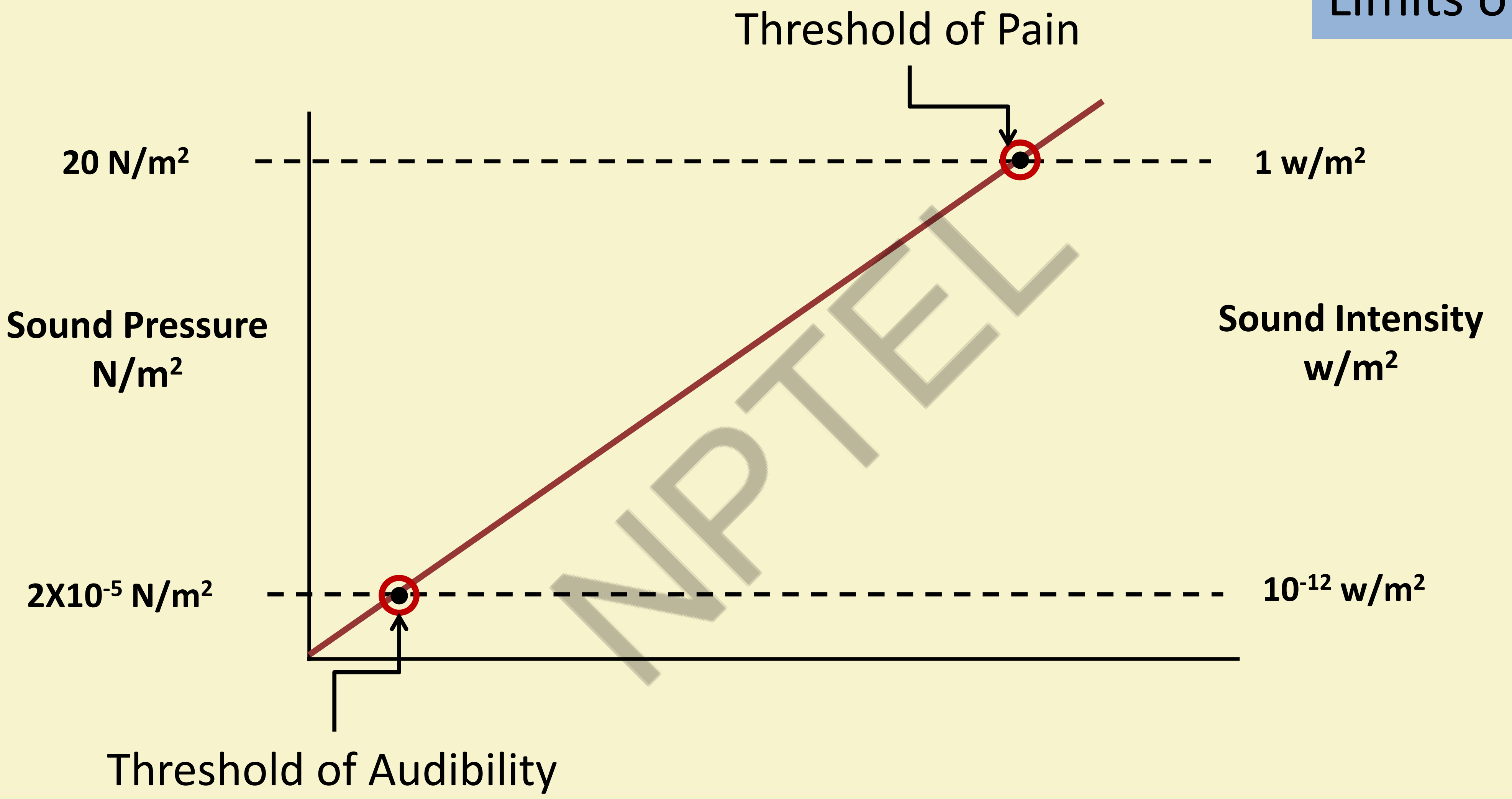
$$\int \delta R = \int \frac{\delta S}{S}$$

$$R = \log(S) + C$$

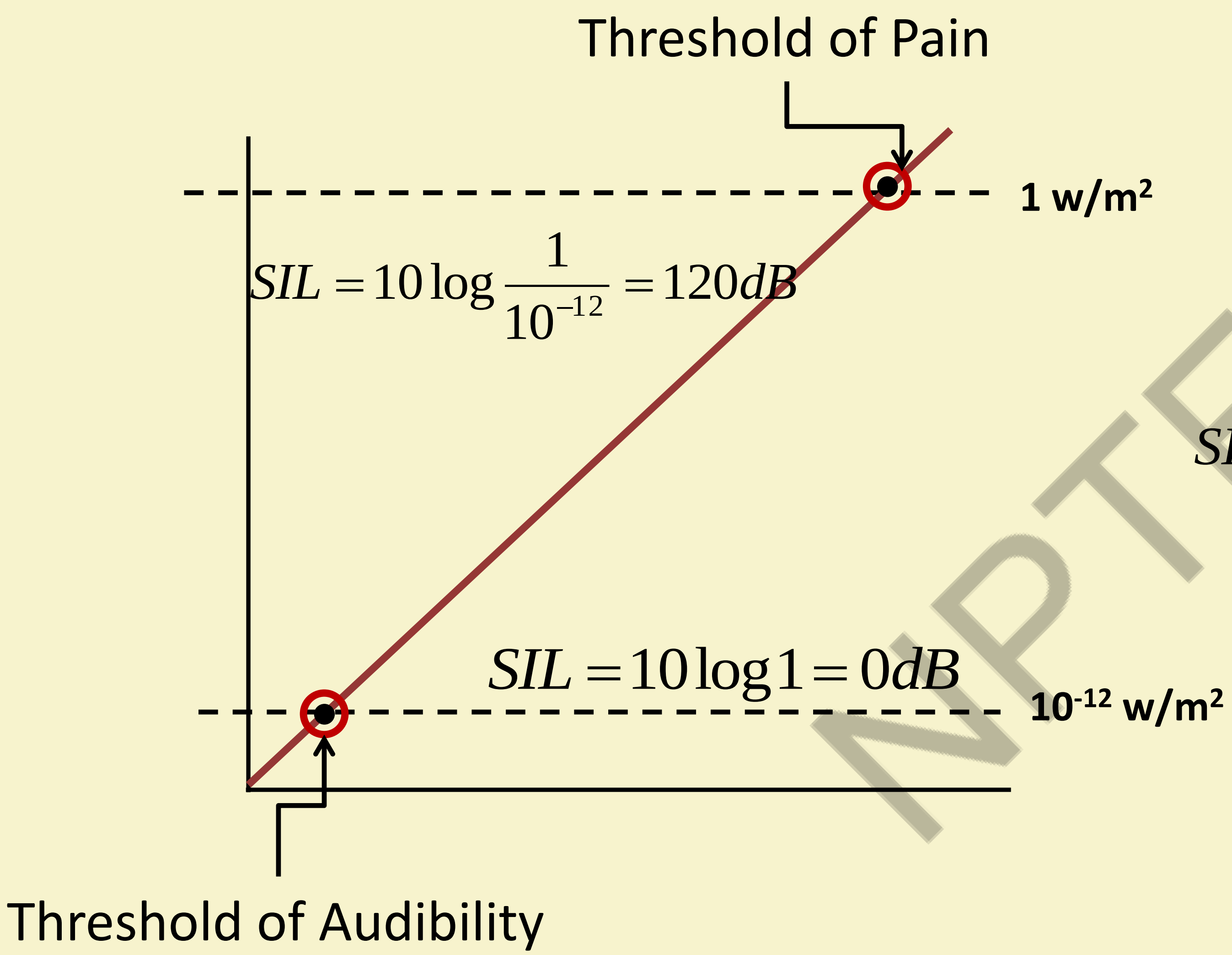
$$R = k.\log(S)$$

We hear Logarithmic

Limits of Audibility



Sound Intensity Level



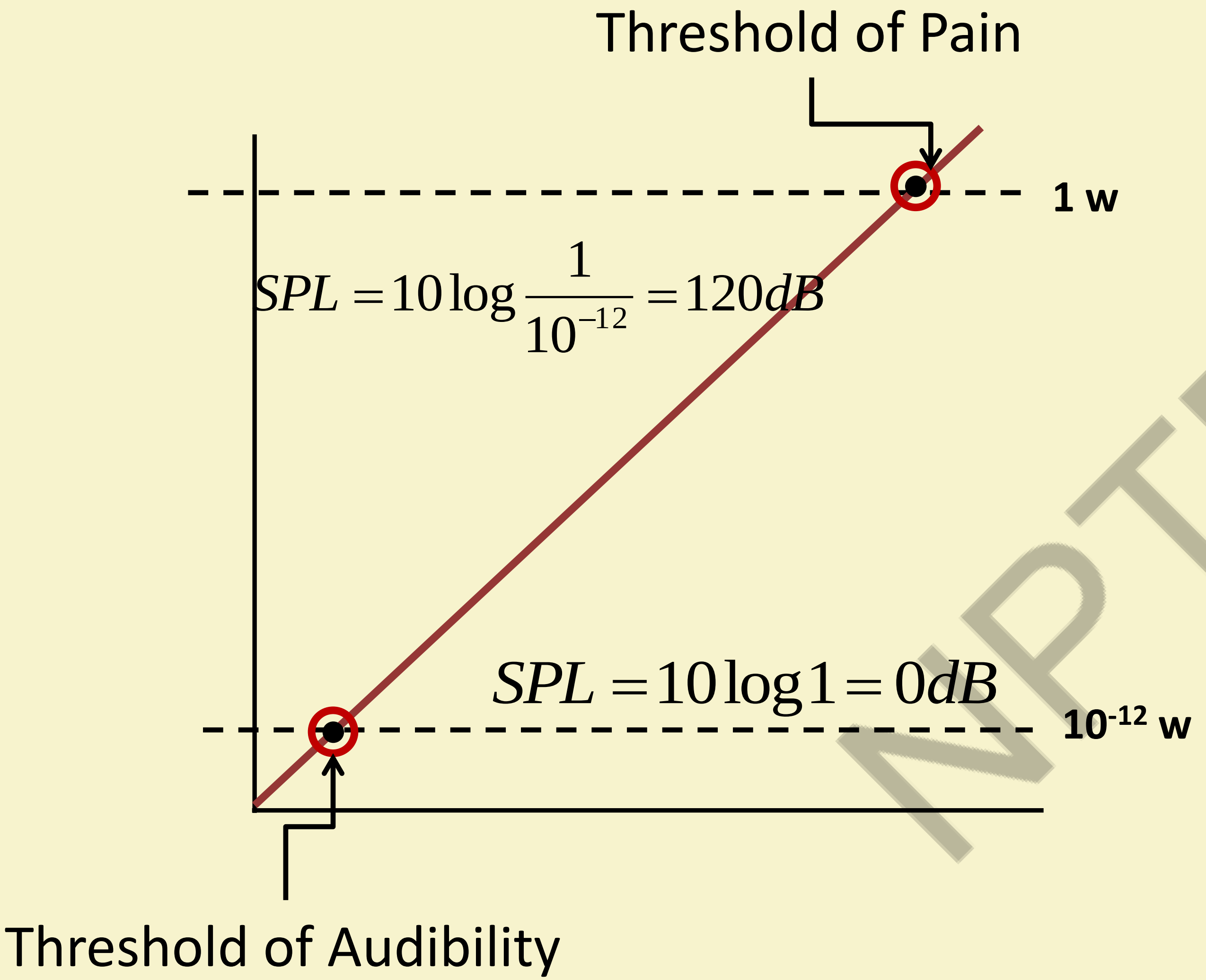
Sound Intensity Level

$$SIL = \log\frac{I}{I_{ref}} \text{ [bel]} \qquad SIL = 10\log\frac{I}{I_{ref}} \, decibel$$

I = Actual Sound Intensity in W/m^2

$I_{ref} = 10^{-12}\ W/m^2$

Sound Power Level



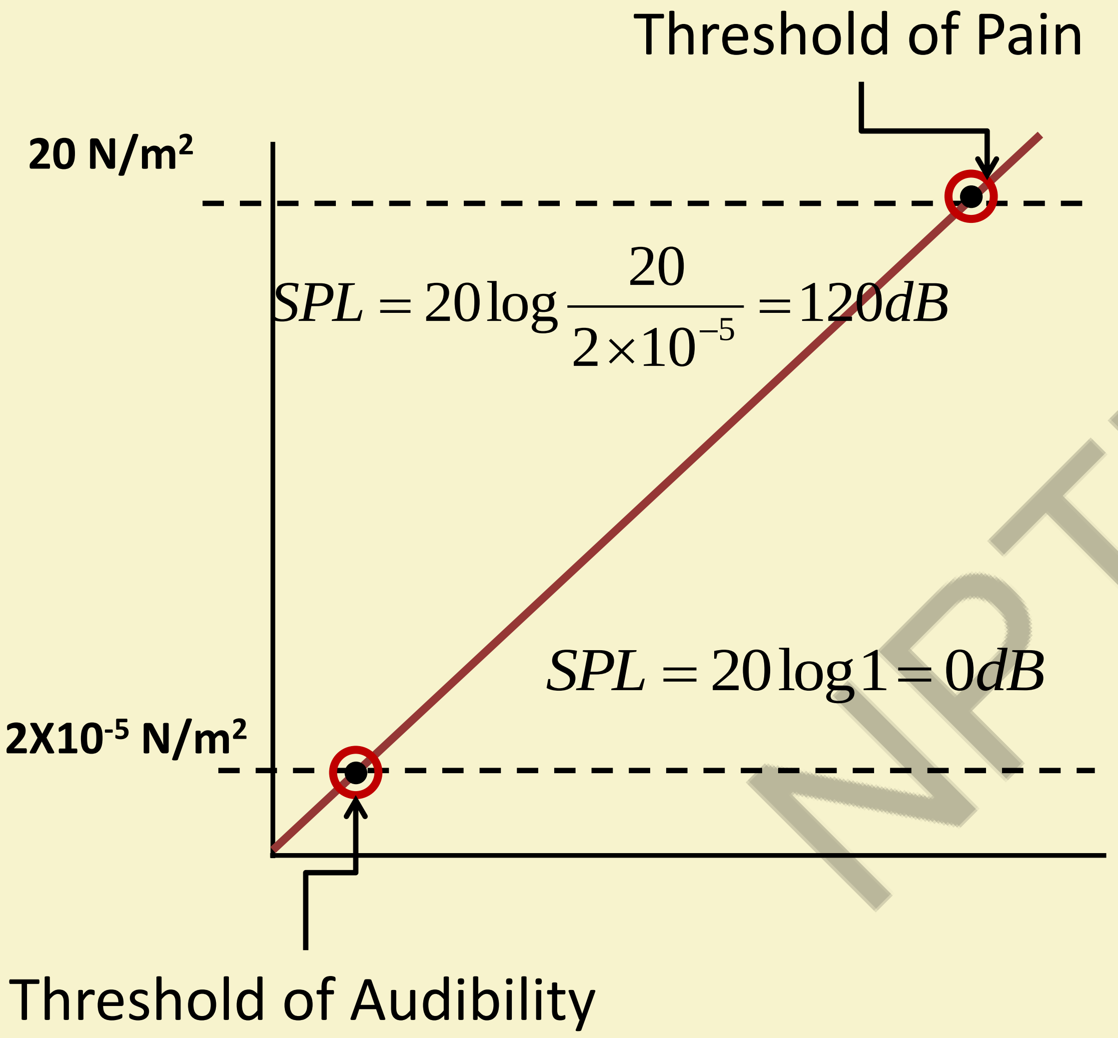
Sound Power Level

$$SPL = 10\log\frac{W}{W_{ref}}$$

W= Actual Sound Power in W

$W_{ref} = 10^{-12}$ W

Sound Pressure Level



$$\text{Intensity} \propto (\text{Pressure})^2$$

Sound Pressure Level

$$SPL = 20\log\frac{P}{P_{ref}}$$

P = Actual Sound Pressure in Pa

P_{ref} = 2x10^{-5} Pa = 20μPa

Sound Level Meter

Alexander Graham Bell

Sound Intensity to Sound Level Conversion

Sound Intensity Level from Sound Intensity

$$\boxed{L = 10\log\frac{I}{I_{ref}}}$$

If Sound Intensity is 0.005 w/m^2

So, replacing: $I = 0.005\ W/m^2$ & $I_{ref} = 10^{-12}\ W/m^2$

$$L = 10\log\frac{0.005}{10^{-12}} = 10\log(5^9) = 10\times 9.698 = 97dB$$

Sound Level to Intensity Conversion

Sound Intensity from Sound Intensity Level

$$\boxed{L = 10\log\frac{I}{I_{ref}}} \Rightarrow \log\frac{I}{I_{ref}} = \left(\frac{L}{10}\right) \Rightarrow \frac{I}{I_{ref}} = 10^{\left(\frac{L}{10}\right)} \Rightarrow \boxed{I = I_{ref} \times 10^{\left(\frac{L}{10}\right)}}$$

If SIL is 65 dB

So, replacing: L = 65 db

$$I = I_{ref} \times 10^{\left(\frac{L}{10}\right)} = 10^{-12} \times 10^{\left(\frac{65}{10}\right)} = 10^{-12} \times 10^{6.5} = 3.162 \times 10^{-6} W/m^2$$

Range of Sound Level

Sound Sources	Sound Level in dB
Sweeping of dry leaves	10
Background noise in TV Studio	20
Library / Bed Room	30 – 40
Residential Zone	50
Normal Conversation	60
Vacuum Cleaner (1m)	70
Heavy City Traffic	80
Pneumatic Drill	90 – 100
Discotheque	100 – 110
Jet Aircraft (100m)	140

Addition of Sound Levels

Source-1

L_1

$$L_1 = 10\log\frac{I_1}{I_{ref}} \Rightarrow I_1 = I_{ref}\times 10^{\left(\frac{L_1}{10}\right)}$$

Sound Intensities can be Arithmetically Added

$$I_{Total} = (I_1 + I_2) = I_{ref}\times\left[10^{\left(\frac{L_1}{10}\right)} + 10^{\left(\frac{L_2}{10}\right)}\right]$$

L_2

$$L_2 = 10\log\frac{I_2}{I_{ref}} \Rightarrow I_2 = I_{ref}\times 10^{\left(\frac{L_2}{10}\right)}$$

Source-2

$$L_{Total} = 10\log\frac{I_{Total}}{I_{ref}} = 10\log\left[10^{\left(\frac{L_1}{10}\right)} + 10^{\left(\frac{L_2}{10}\right)}\right]$$

So, if two different SPL of L_1 & L_2 are added,
Then the resultant SPL will be given by:

$$\boxed{L_{Total} = 10\log\left[10^{\left(\frac{L_1}{10}\right)} + 10^{\left(\frac{L_2}{10}\right)}\right]}$$

Addition of Sound Levels

If both the sound source are producing same intensity

Then, $L_1 = L_2 = L$

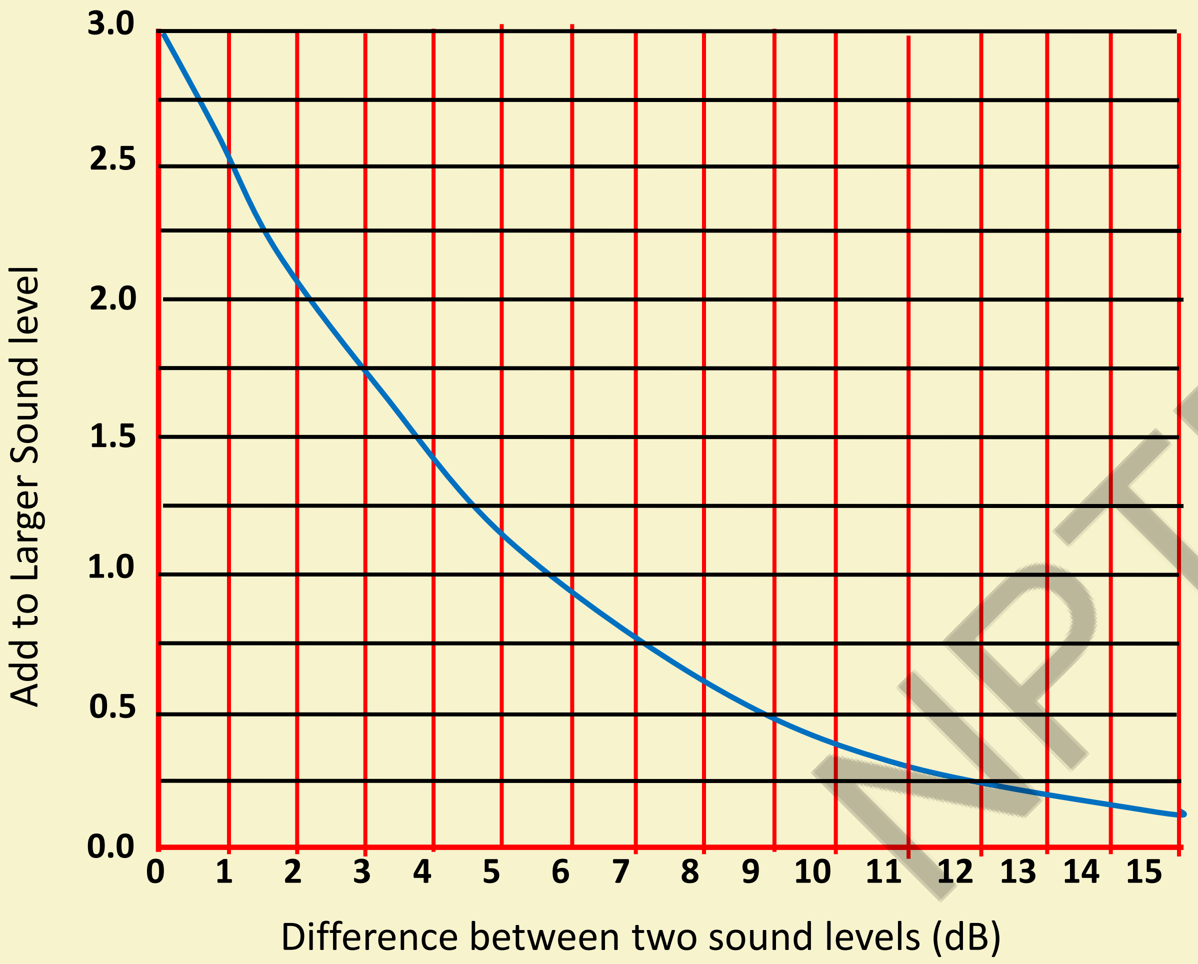
$I_1 = I_2 = I$

$$I_{Total} = (I_1 + I_2) = 2I$$

$$L_{Total} = 10\log\frac{I_{Total}}{I_{ref}} = 10\log\frac{2I}{I_{ref}} = 10\log\frac{I}{I_{ref}} + 10\log(2)$$

$$L_{Total} = L + 3dB$$

Addition of Sound Levels



How to read this graph??

Addition of Sound Levels

$$L_{Total} = 10\log\left[10^{\left(\frac{L_1}{10}\right)} + 10^{\left(\frac{L_2}{10}\right)}\right]$$

Let

L_1 = 60 dB & L_2 = 65 dB

$$L_{Total} = 10\log\left[10^{\left(\frac{60}{10}\right)} + 10^{\left(\frac{65}{10}\right)}\right] = 10\log\left(10^{6} + 10^{6.5}\right) = 66.2dB$$

66.2 = 65 + 1.2

Let

L_1 = 90 dB & L_2 = 95 dB

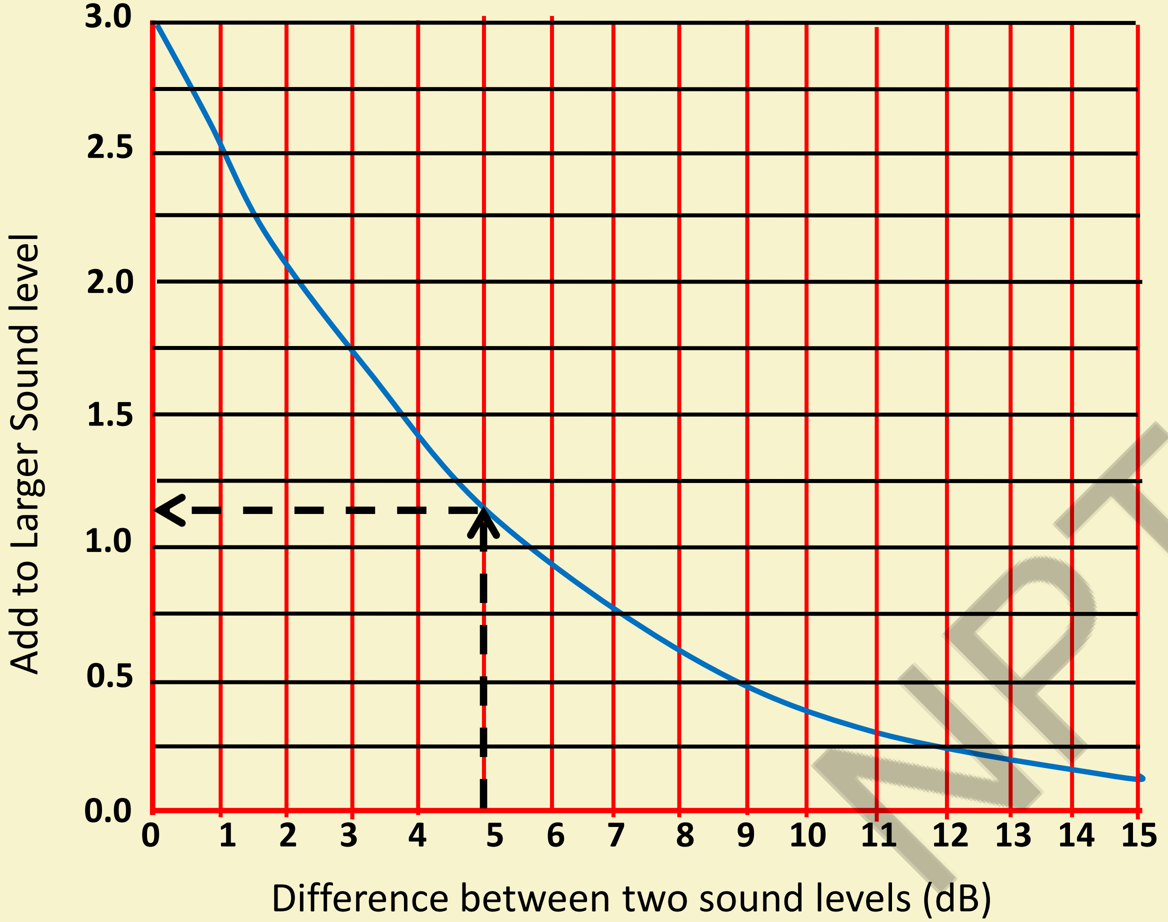
$$L_{Total} = 10\log\left(10^{9} + 10^{9.5}\right) = 96.2dB$$

96.2 = 95 + 1.2

Difference between two sound levels = 5dB

Add 1.2dB to the larger Sound Level

Addition of Sound Levels



Difference between two sound levels = 5dB

Add 1.2dB to the larger Sound Level

Addition of Sound Levels

In case of Many Sound Levels and/ or intensities are added together

$$L_{Total} = 10\log\left[10^{\left(\frac{L_1}{10}\right)} + 10^{\left(\frac{L_2}{10}\right)} + 10^{\left(\frac{L_3}{10}\right)} + \ldots. + 10^{\left(\frac{L_n}{10}\right)}\right]$$

$$\boxed{L_{Total} = 10\log\sum_{i=1}^{n} 10^{\left(\frac{Li}{10}\right)}}$$

Home Work

Can you convert the following physical parameters to its related Sound Levels

1. Sound Intensity of 0.004 W/m^2
2. Sound Pressure of 1.2 MPa

If two different source of sound having dB level: 58dB & 62 dB are added, What will be the resultant Sound Level?

1. Compute using mathematical formula
2. Check your result from the graph

Bibliography

1. **Acoustics in the Built Environment**, Duncan Templeton, Architectural Press; 2nd Edition

2. **Architectural Acoustics**, K.B.Genn, Burel & Kjaer, 2nd Edition

3. **Architectural Acoustics,** Marshall Long, El Sevier, Academic Press,

4. **Mechanical and Electrical Equipment for Buildings**, Walter T. Grondzik, Alison G. Kwok, Benjamin Stein and John S. Reynolds, John Wiley & Sons, Inc. (11th Edition) [Part-IV]

End of Lecture 04: Sound Pressure and Intensity Level

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Architectural Acoustics

Lecture 05: Near & Far Field Propagation and Loudness

Dr. Shankha Pratim Bhattacharya
Department of Architecture & Regional Planning

Learning Objective

Differentiate between Near and Far Field Propagation of Sound

Correlate among Frequency, Sound Level and Loudness of Sound

Intensity is Power per unit Area

$$\text{Intensity} = \frac{\text{Power}}{\text{Area}} = \frac{\text{Energy}}{\text{Time}} \times \frac{1}{\text{Area}} = \frac{\text{Energy}}{\text{Time}} \times \frac{\text{Length}}{\text{Volume}}$$

$$\text{Intensity} = \frac{\text{Energy}}{\text{Volume}} \times \frac{\text{Length}}{\text{Time}} = \frac{\text{Energy}}{\text{Volume}} \times \text{Wave Velocity}$$

$$\text{Energy} = \frac{1}{2} \times \text{Mass} \times V_{max}^2 = \frac{1}{2} m (A\omega)^2$$

$$\text{Intensity} = \frac{\text{Energy}}{\text{Volume}} \times \text{Wave Velocity}$$

$$\text{Volume} = \frac{\text{Mass}}{\text{Density}} = \frac{m}{\rho}$$

Sound Intensity

$$\text{Intensity} = \frac{\text{Energy}}{\text{Volume}} \times \text{Wave Velocity}$$

$$\text{Energy} = \frac{1}{2} \times \text{Mass} \times V_{max}^2 = \frac{1}{2} m(A\omega)^2$$

$$\text{Volume} = \frac{\text{Mass}}{\text{Density}} = \frac{m}{\rho}$$

$$\text{Intensity} = \frac{\text{Energy}}{\text{Volume}} \times \text{Wave Velocity} = \frac{1}{2} m(A\omega)^2 \times \frac{\rho}{m} \times c$$

$$\boxed{\text{Intensity} = \frac{1}{2} \rho\, c(A\omega)^2}$$

Acoustical Impedance

$$\text{Intensity} = \frac{1}{2}\rho\, c(A\omega)^2 \quad \Rightarrow \quad I = \frac{1}{2}\rho c(A\omega)^2 = \frac{1}{2} \times \frac{(\rho c A\omega)^2}{\rho c}$$

$$\boxed{I = \frac{1}{2} \times \frac{P_0^2}{z}}$$

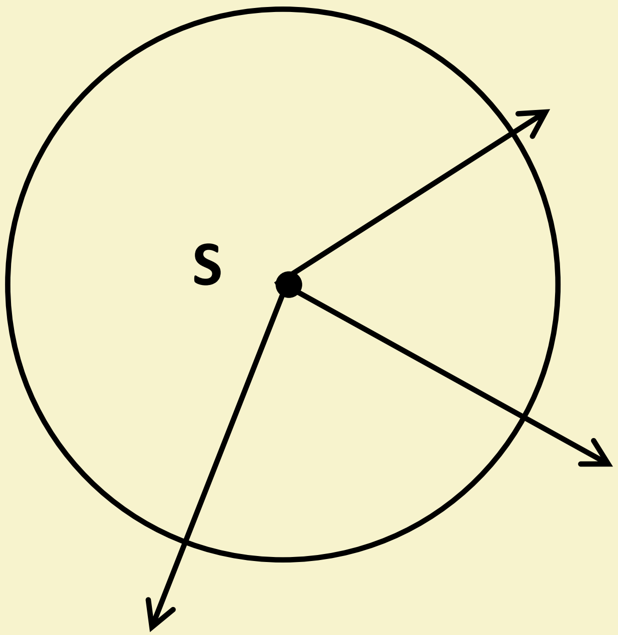
Where, P_0 is Pressure Amplitude of Sound Wave Propagation

$$P_0 = \rho\, c\, A\, \omega \quad \Rightarrow \quad \frac{Kg}{m^3} \times \frac{m}{s} \times m \times \frac{rad}{s} = \frac{Kg}{m^3} \times \frac{m}{s^2} \times m = \frac{Kg}{m^2} \times \frac{m}{s^2} = Kg \times \frac{m}{s^2} \times \frac{1}{m^2} = \frac{N}{m^2} = Mpa$$

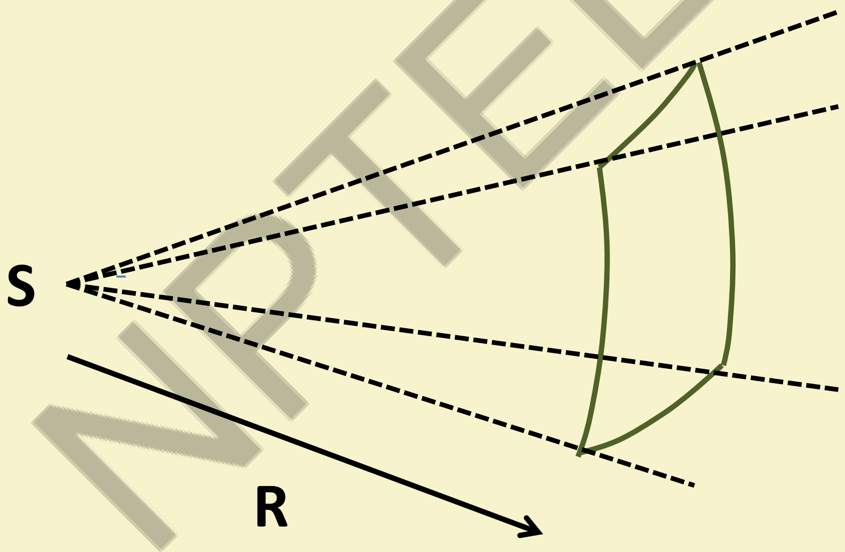
Specific Acoustical Impedance (z): Product of Medium Density (ρ) & Wave Velocity (c)

Spherical Propagation

Point Source >>>>>>> Spherical Propagation



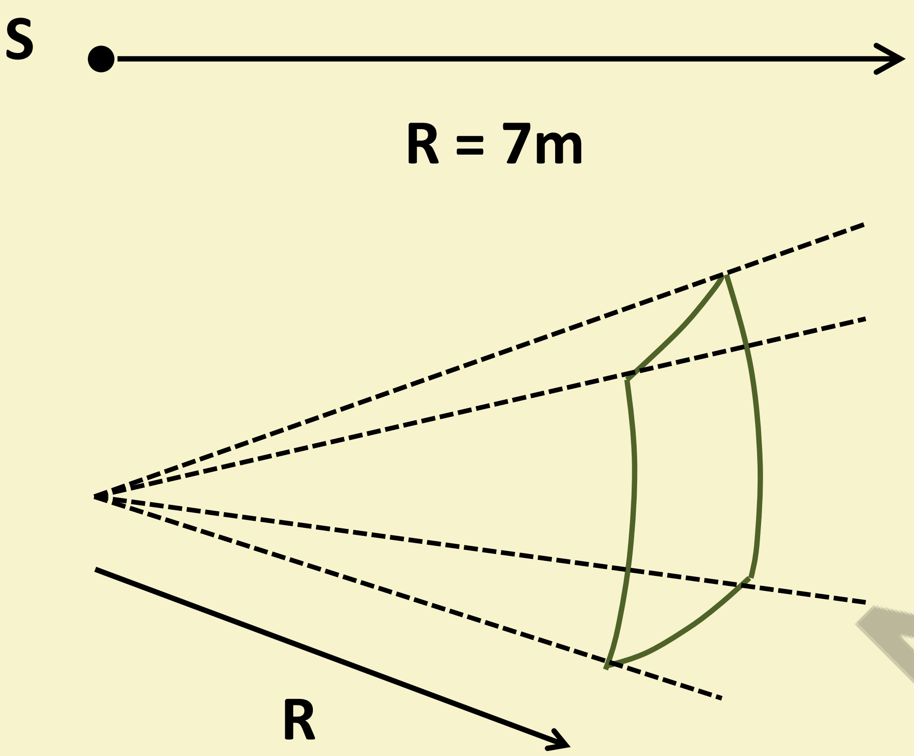
$$\text{Intensity} = \frac{\text{Watt output}}{\text{Surface Area of the Sphere}}$$



$$\text{Intensity} = \frac{W}{4\pi R^2}$$

Spherical Propagation

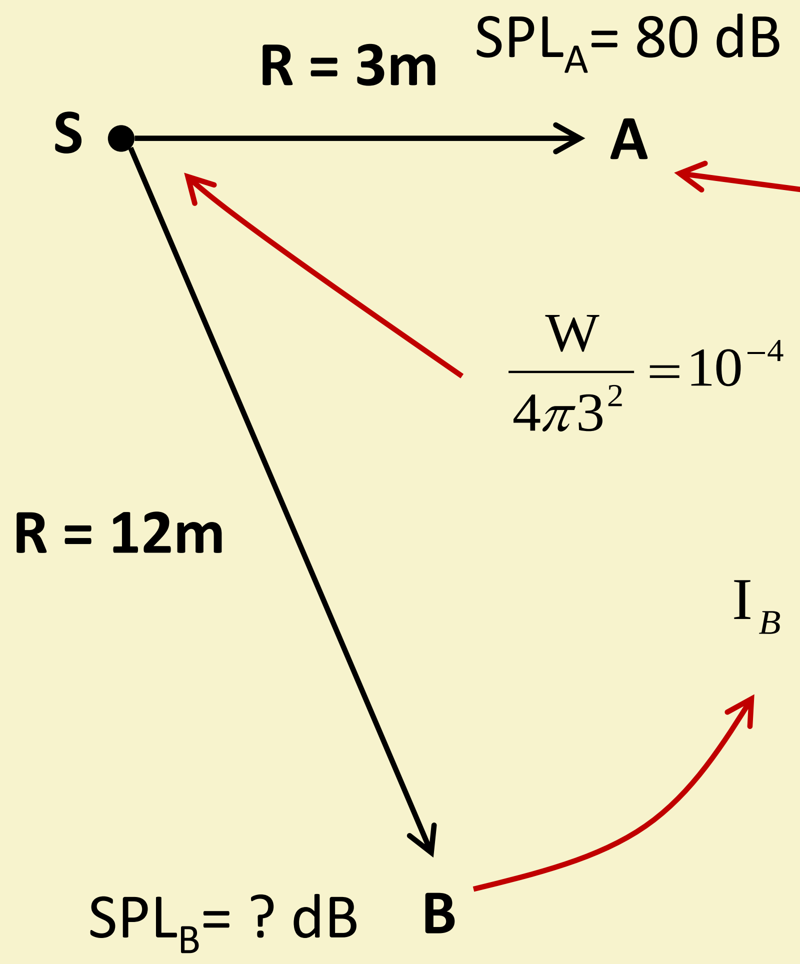
Sound Output = 0.0005 Watt



$$\text{Intensity} = \frac{W}{4\pi r^2} = \frac{0.0005}{4\times\pi\times 7^2} = 8.12\times10^{-7}\,\text{W/m}^2$$

$$\text{SPL} = 10\log\frac{8.12\times10^{-7}}{10^{-12}} = 59\text{dB}$$

Spherical Propagation



$$SPL_A = 10\log\frac{I_A}{10^{-12}} = 80\text{dB} \Rightarrow I_A = 10^{-12} \times 10^{8} = 10^{-4} W/m^2$$

$$\frac{W}{4\pi 3^2} = 10^{-4} \Rightarrow W = 4\pi 3^2 \times 10^{-4} = 0.0113W$$

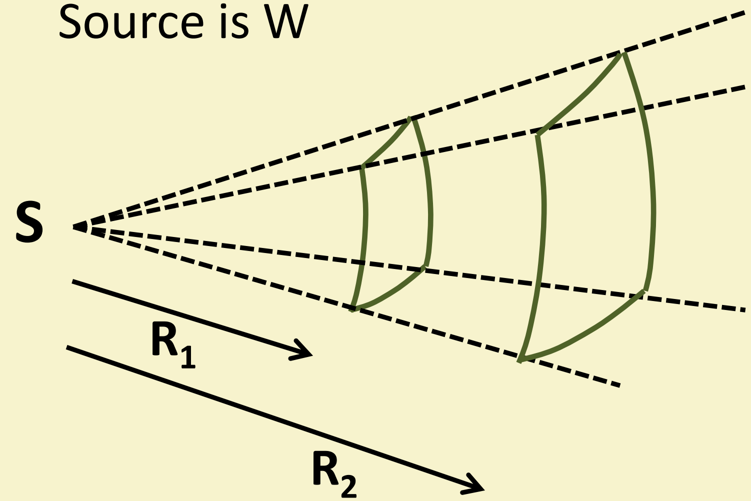
$$I_B = \frac{W}{4\pi R^2} = \frac{0.0113}{4\pi 12^2} = 6.25 \times 10^{-6} W/m^2$$

$$\Downarrow$$

$$SPL_B = 10\log\frac{I_B}{10^{-12}} = 10\log\frac{6.25\times 10^{-6}}{10^{-12}} = 68\text{dB}$$

Spherical Propagation

Sound Output from Source is W



$$I_1 = \frac{W}{4\pi R_1^2} \Rightarrow SPL_1 = 10\log\frac{I_1}{I_{ref}}$$

$$I_2 = \frac{W}{4\pi R_2^2} \Rightarrow SPL_2 = 10\log\frac{I_2}{I_{ref}}$$

$SPL_1 > SPL_2$

$$SPL_1 - SPL_2 = 10\log\frac{I_1}{I_{ref}} - 10\log\frac{I_2}{I_{ref}} = 10\log\left(\frac{I_1}{I_{ref}} \times \frac{I_{ref}}{I_2}\right)$$

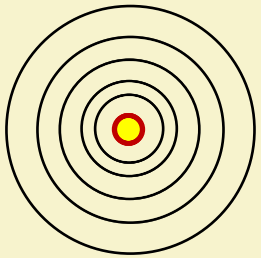
$$SPL_1 - SPL_2 = 10\log\left(\frac{I_1}{I_2}\right) = 10\log\left(\frac{W}{4\pi R_1^2} \times \frac{4\pi R_2^2}{W}\right)$$

$$\boxed{SPL_1 - SPL_2 = 10\log\left(\frac{R_2}{R_1}\right)^2 = 20\log\left(\frac{R_2}{R_1}\right)}$$

If, $R_2 = 2R_1$ $\quad SPL_1 - SPL_2 = 20\log\left(\frac{R_2}{R_1}\right) = 20\log(2) = 6dB$

Spherical & Cylindrical Propagation

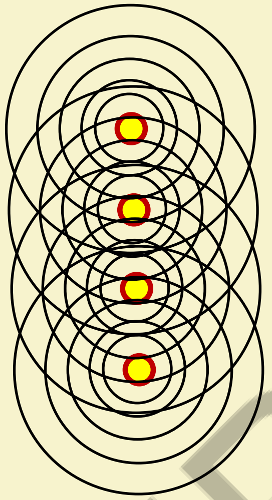
Point Source

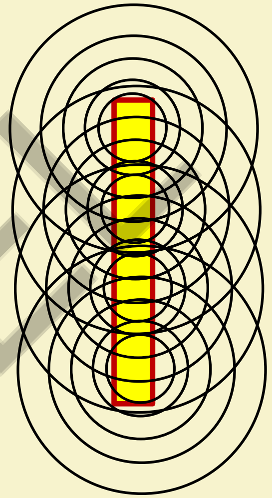


Spherical Propagation

Single Loudspeaker
Human Voice
Noise from a Car

Multiple Point Source
Line Source

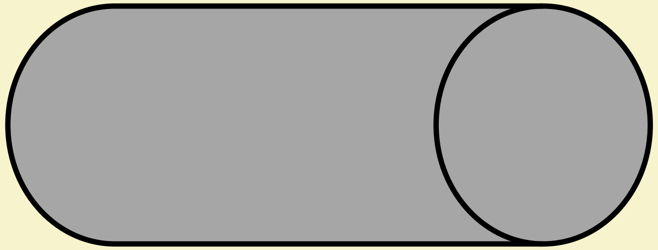




Cylindrical Propagation

Road Traffic Noise
Railway
Array of Loudspeakers

Cylindrical Propagation



Radius = R

Length = L

$$\text{Intensity} = \frac{\text{Watt output}}{\text{Surface Area of the Cylinder}}$$

$$\boxed{\text{Intensity} = \frac{W}{2\pi RL}}$$

Length of the line source 100m

Sound output = 0.005 Watt

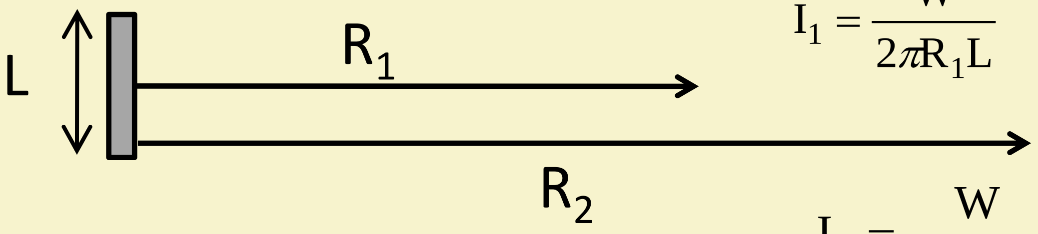
SPL at 7m from the Line Source=?

$$\text{Intensity} = \frac{W}{2\pi RL} = \frac{0.005}{2\pi \times 7 \times 100} = 1.137 \times 10^{-6} W/m^2$$

$$L = 10\log\frac{I}{I_{ref}} = 10\log\frac{1.137 \times 10^{-6}}{10^{-12}} = 60.5dB$$

Cylindrical Propagation

Sound Output from Source is W, having length =L



$$I_1 = \frac{W}{2\pi R_1 L}$$

$$I_2 = \frac{W}{2\pi R_2 L}$$

$SPL_1 > SPL_2$

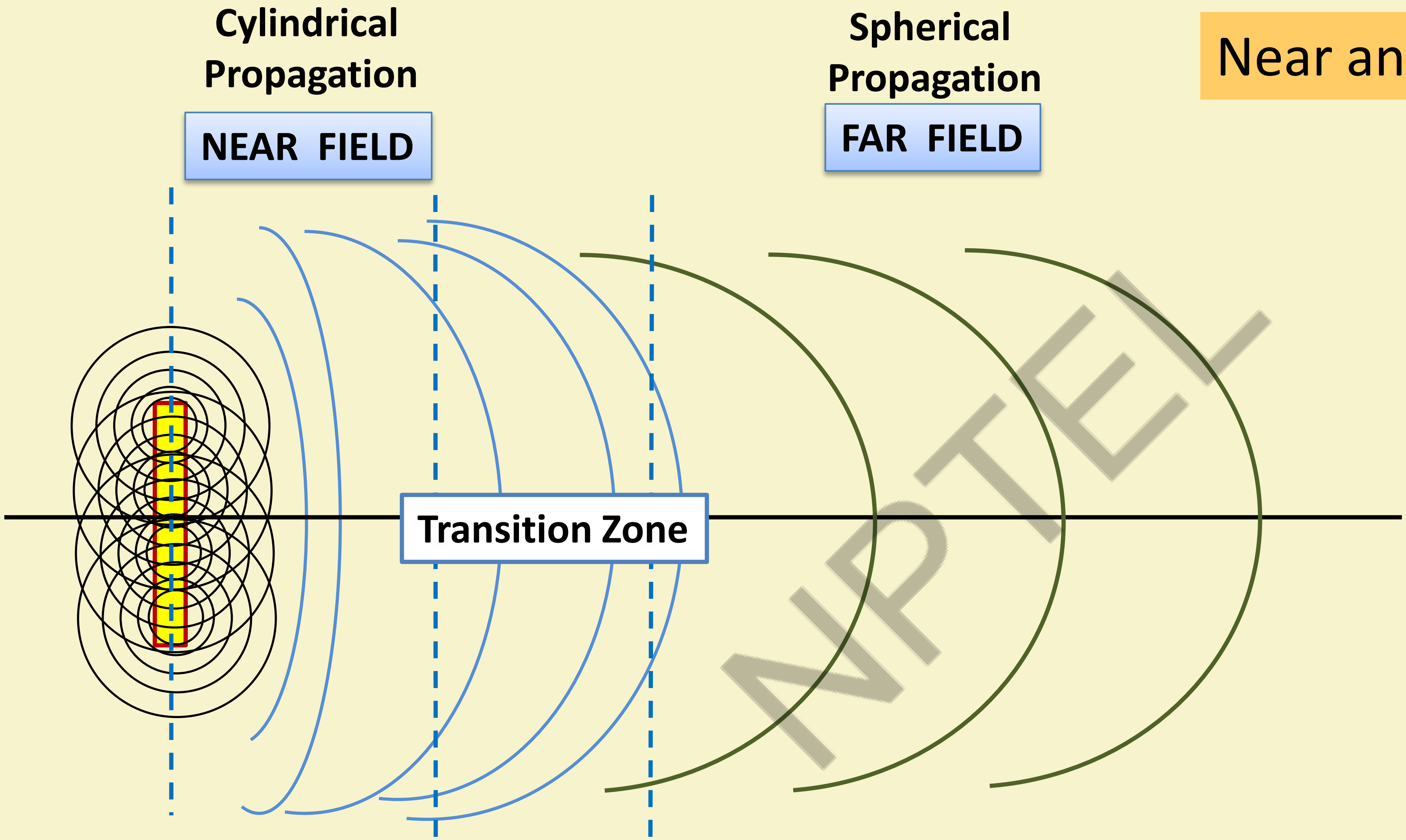
$$SPL_1 - SPL_2 = 10\log\frac{I_1}{I_{ref}} - 10\log\frac{I_2}{I_{ref}} = 10\log\left(\frac{I_1}{I_{ref}} \times \frac{I_{ref}}{I_2}\right)$$

$$SPL_1 - SPL_2 = 10\log\left(\frac{I_1}{I_2}\right) = 10\log\left(\frac{W}{2\pi R_1 L} \times \frac{2\pi R_2 L}{W}\right)$$

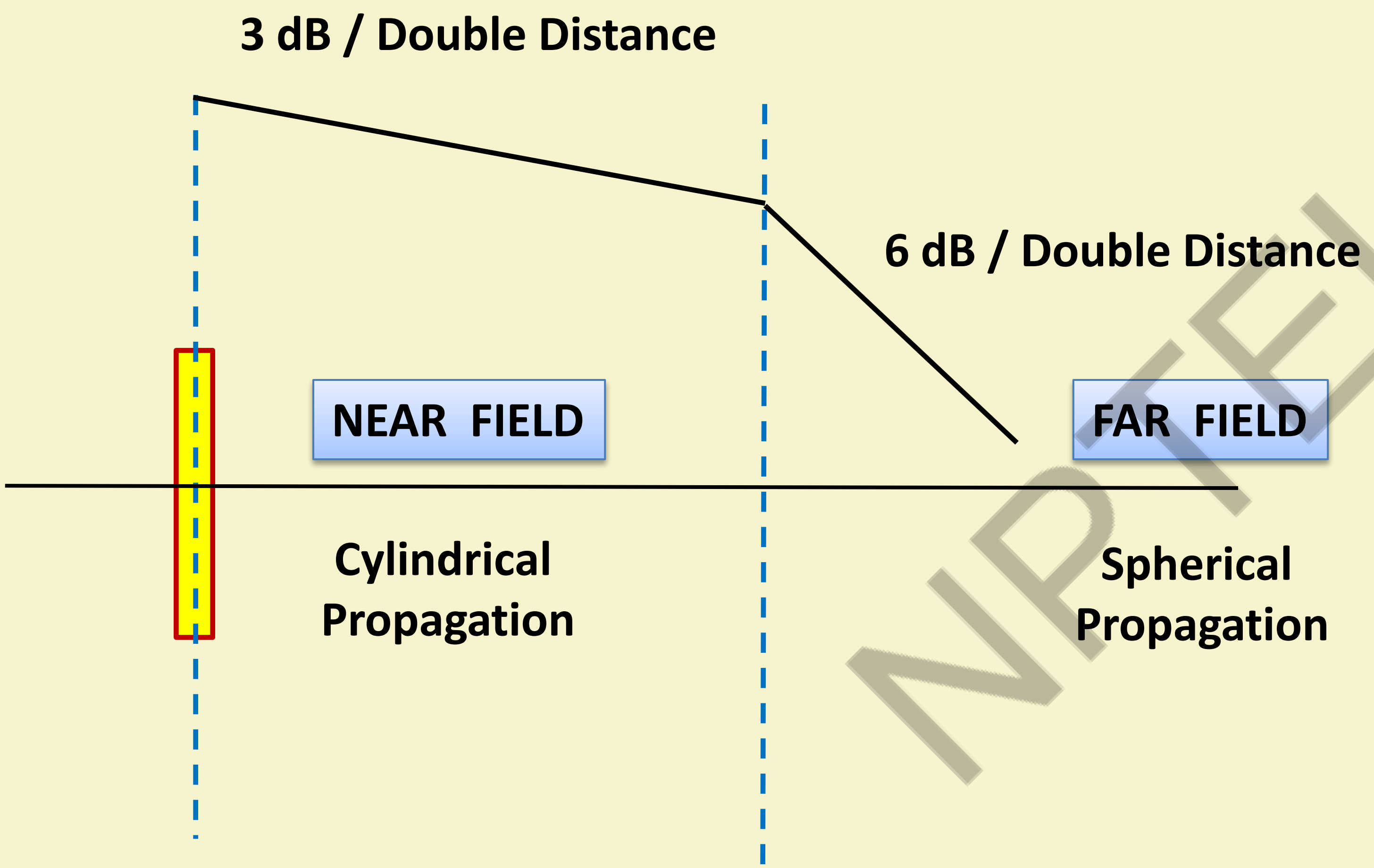
$$SPL_1 - SPL_2 = 10\log\left(\frac{R_2}{R_1}\right)$$

If, $R_2 = 2R_1$ $\quad SPL_1 - SPL_2 = 10\log\left(\frac{R_2}{R_1}\right) = 10\log(2) = 3dB$

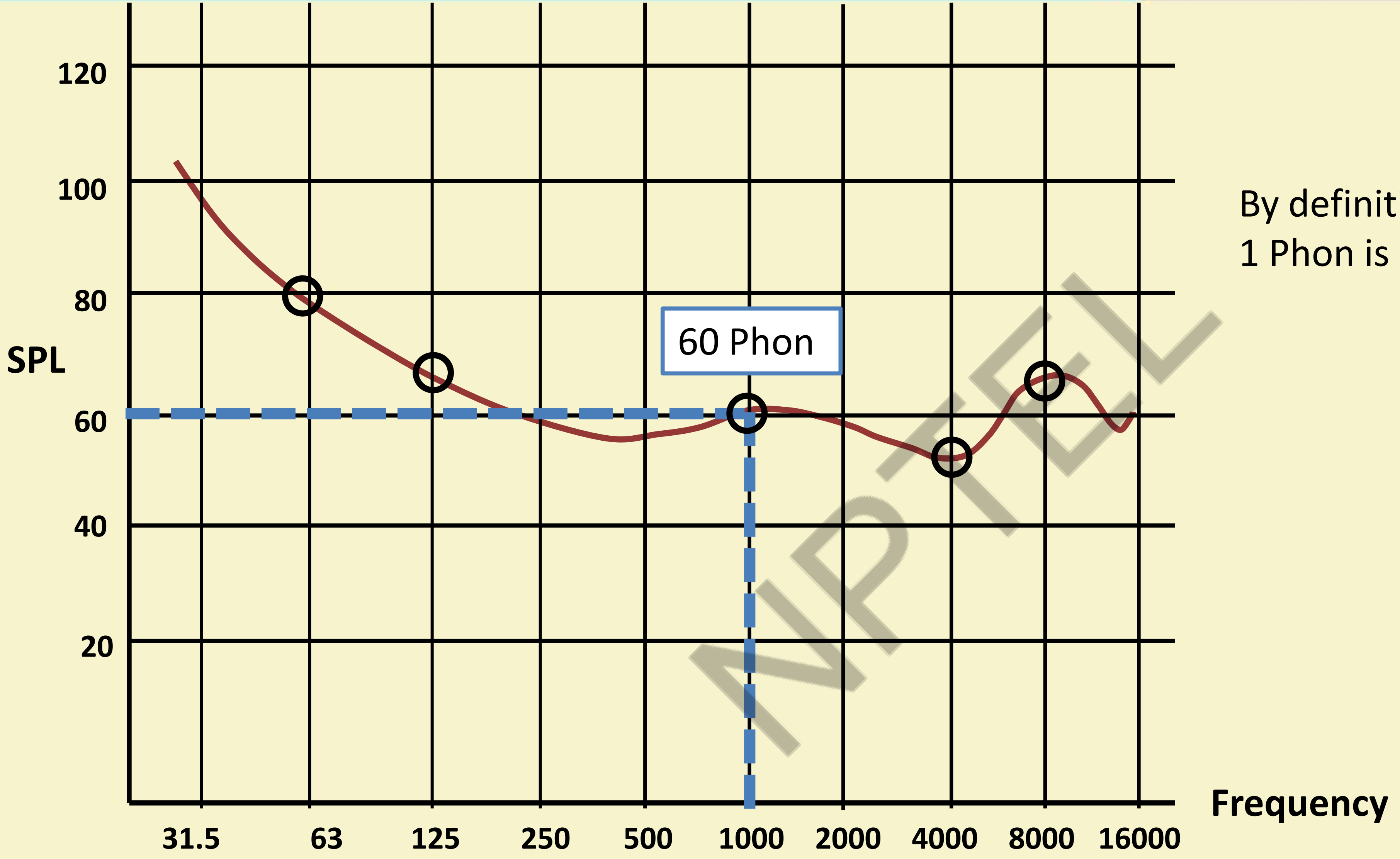
Near and Far Field Propagation



Near and Far Field Propagation

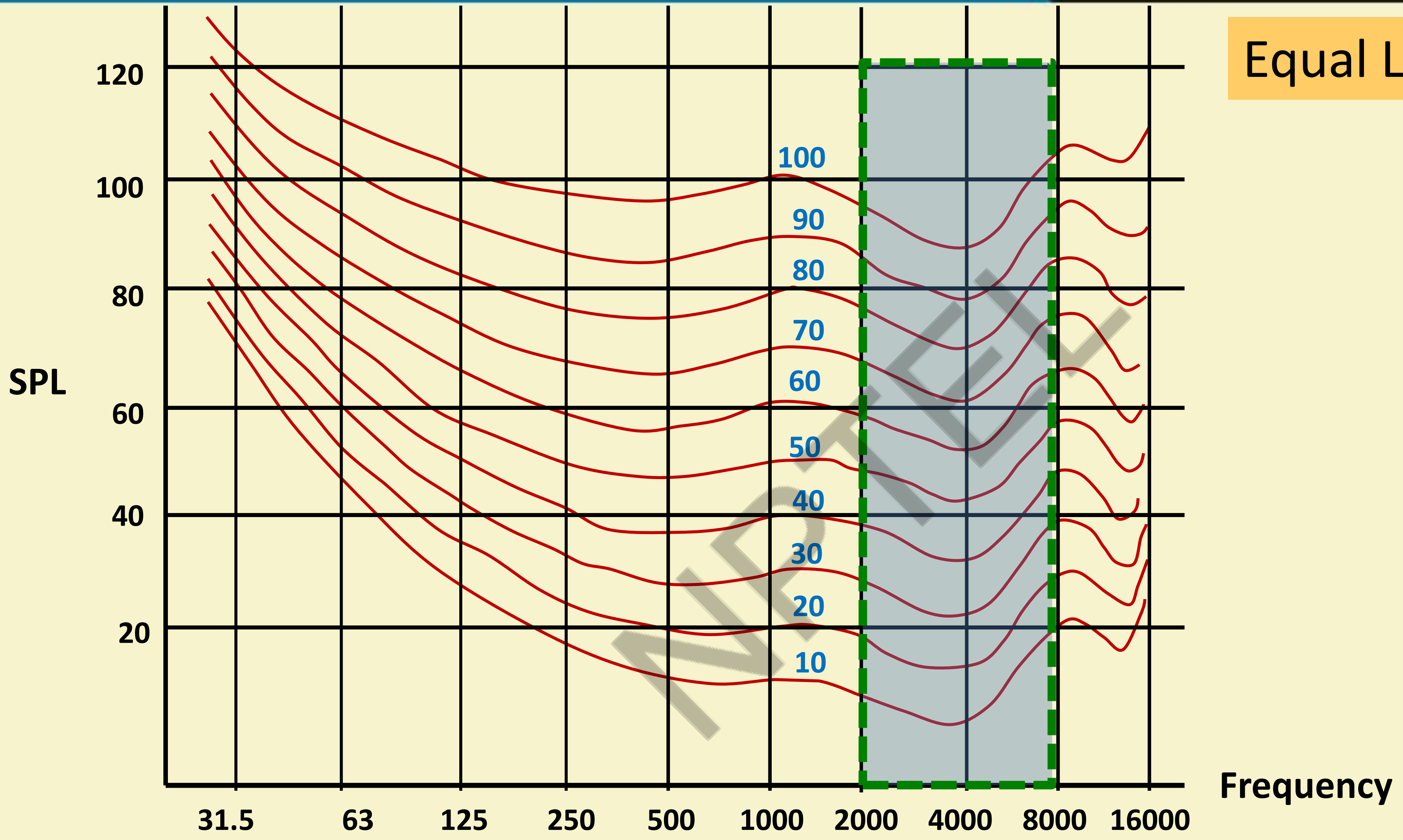


Loudness

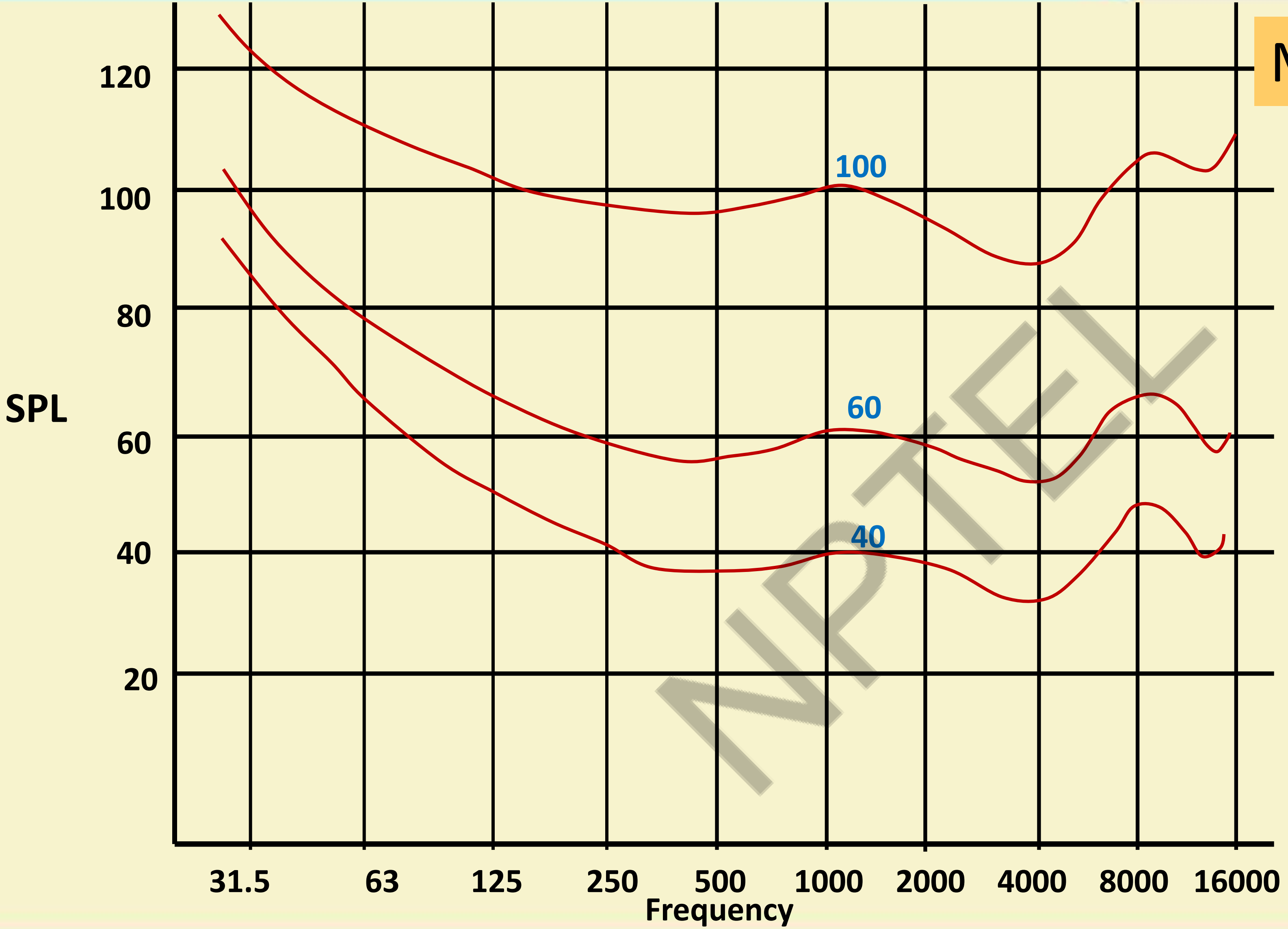


By definition,
1 Phon is equivalent to 1 dB at 1000 Hz

Equal Loudness Contour



Measurement of Loudness



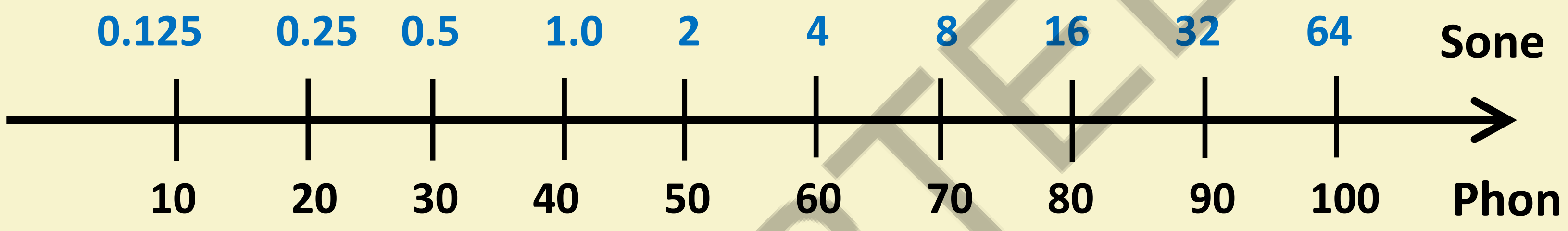
If two sources produce Loudness of 40 and 60 Phon separately, Then the combine loudness is not be 100 Phon

Measurement of Loudness

A Sone scale is adopted over the Phone and it is more linear.

A loudness of 10 phon increase is given a increase the Sone by 2 multiplication factor.

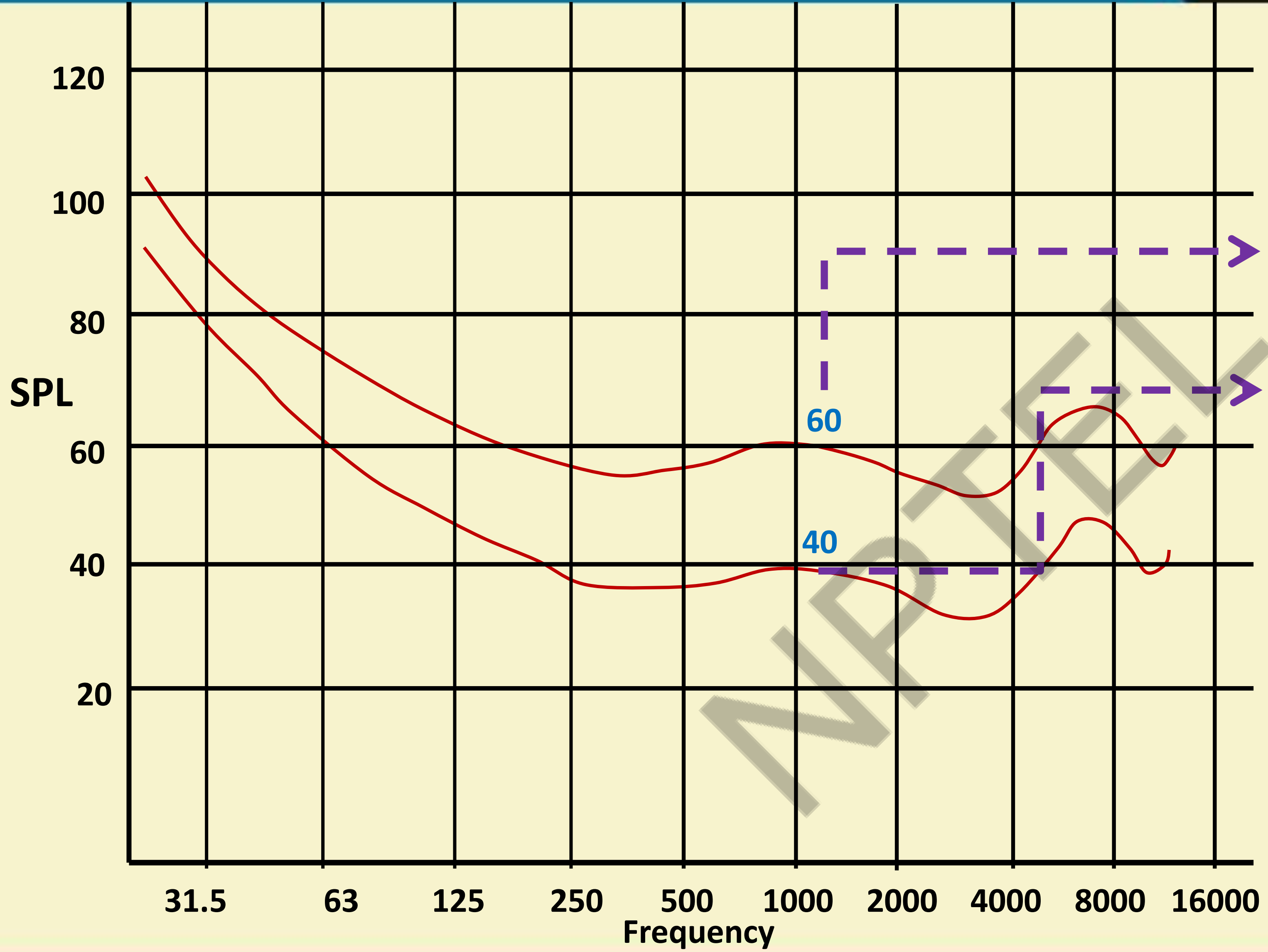
40 Phone is kept as 1 Sone



$$\boxed{\text{Sone} = 2^{\left(\frac{\text{Phon}-40}{10}\right)}}$$

$$\boxed{\text{Phon} = 40 + 33.22 \times \log(\text{Sone})}$$

Measurement of Loudness



$$\text{Sone} = 2^{\left(\frac{\text{Phon}-40}{10}\right)} = 2^{\frac{60-40}{10}} = 4$$

$$\text{Sone} = 2^{\left(\frac{\text{Phon}-40}{10}\right)} = 2^{\frac{40-40}{10}} = 1$$

Total Sone = 5

$$\text{Phon} = 40 + 33.22 \times \log(\text{Sone})$$

$$\text{Phon} = 40 + 33.22\log(5) = 63$$

Home Work

Find the SIL at a distance 10 m from a sound source:
If the SIL at 3m from the source of sound is 75dB

Assume (1) Near Field Propagation

(2) Far Field Propagation

Can you find the resultant loudness of two sounds having following physical parameters

Sound – A: Frequency: 250 Hz , SPL: 60 dB

Sound – B: Frequency: 4 kHz , SPL: 70 dB

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End of Lecture 05: Near & Far Field Propagation and Loudness