520.445/645 - Audio Signal Processing
☞ Topic 2 ☜

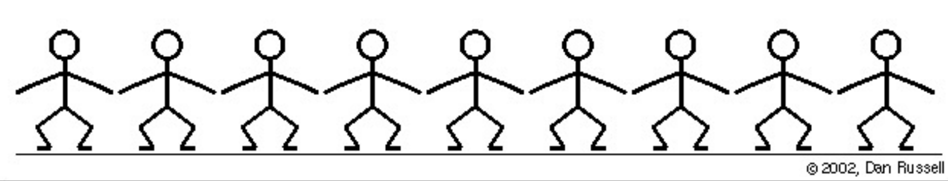
What is sound?

1

1

What is sound?

- Sound is a wave.
- A wave is a traveling disturbance (oscillation) that transfers energy.
- A wave carries energy from place to place



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What is sound?

- Sound waves are mechanical waves
- A mechanical wave requires a medium to travel through (e.g. air or water).
- Note: Electromagnetic waves (like light) do not require a medium

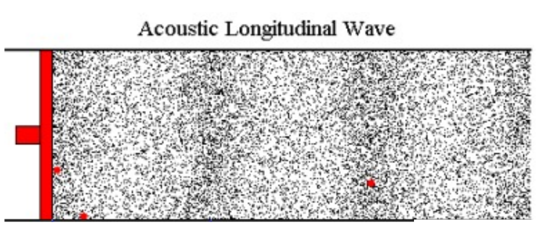
☞ They are not mechanical waves.

3

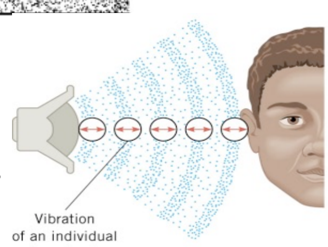
3

Sound is a wave

- Sound is a mechanical wave caused by a vibrating source
- The vibrating source that causes the matter around it to move

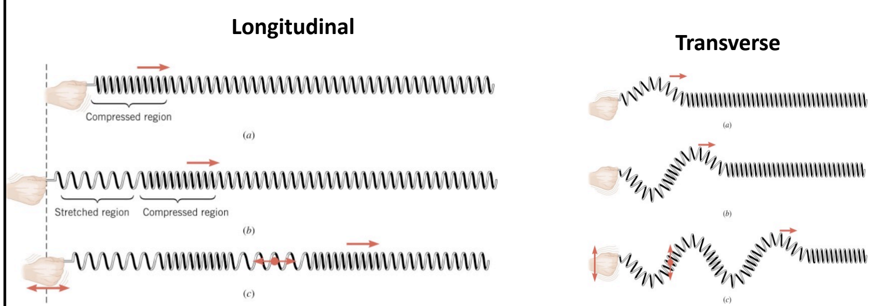


- No sound is produced in a vacuum
  - Matter (air, water, earth) must be present
- Individual air molecules do not move with the wave. A given molecule vibrates back and forth about a fixed location.



4

Waves

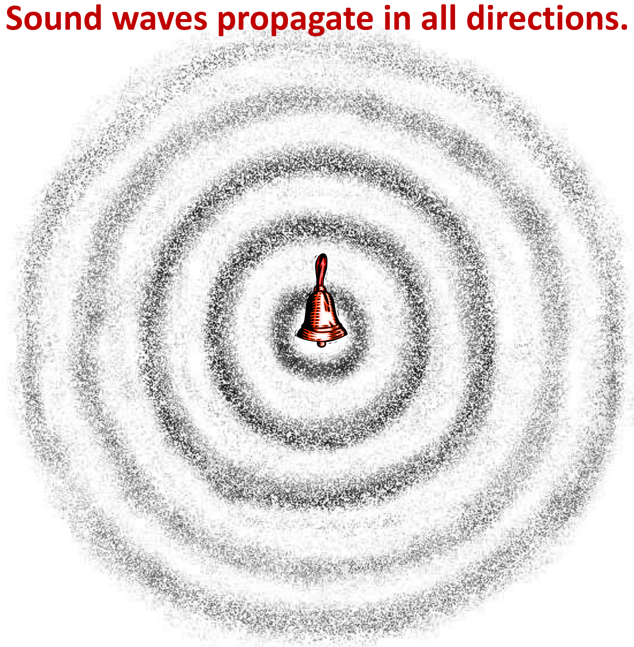


- Sound is a **longitudinal** wave.
  - *the disturbance occurs parallel to the line of travel of the wave*
  - *vs. transverse wave*
    - *disturbance occurs perpendicular to the direction of travel of the wave*
    - *Example: oscillating string, ocean waves*

5

5

Sound waves propagate in all directions.



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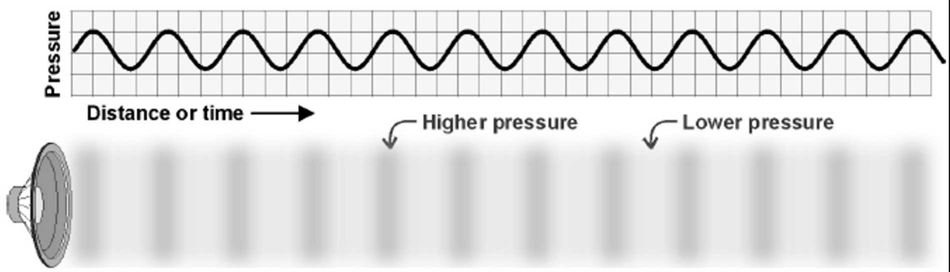
6

Sound waves

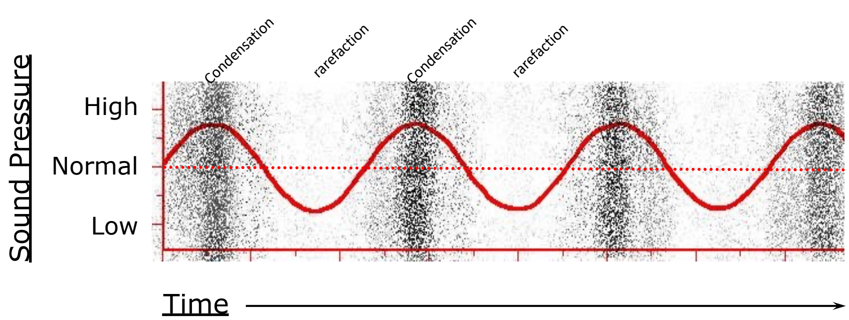
A sound wave is a wave of alternating high-pressure and low-pressure regions of air.



- Vibrating object compresses the air around it (high pressure)
- Pushes air away leaving an area of low pressure (low pressure)
- then compresses again creating a periodic pattern

7

Sound waves



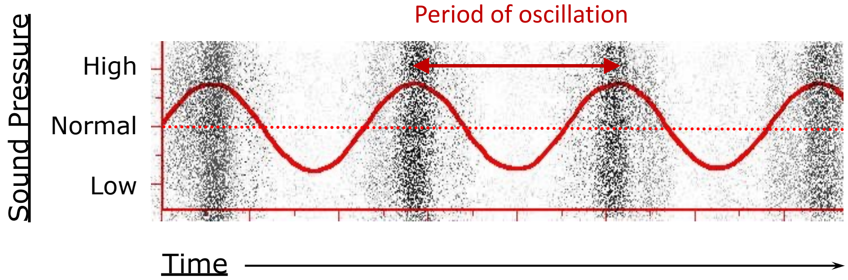
The region of increased pressure is called a *compression*.

The inward motion produces a region known as a *rarefaction,* where the air pressure is slightly less than normal.

8

8

Sound waves



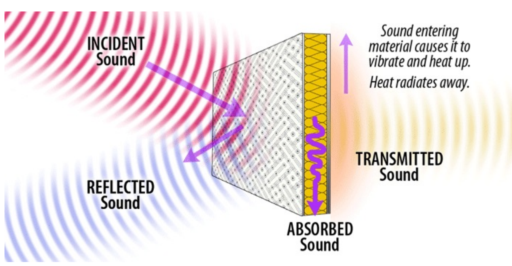
- Motion air particles do not travel, they oscillate around a point in space
- The rate of oscillation is called frequency (f)
  - ✓ denoted in cycles per second (cps) or hertz (Hz).

9

9

Sound waves

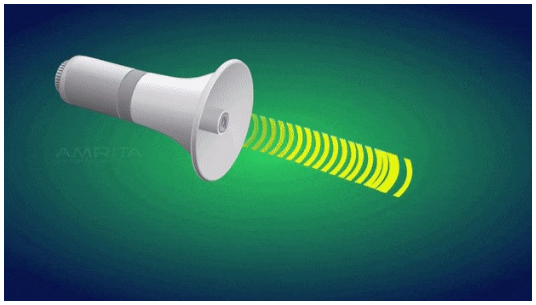
- Like other waves, sound waves can be reflected by surfaces and refracted as they pass from one material to another.
  - The wave doesn't stop when it reaches the end of the medium or when it encounters an obstacle in its path.



- Possible behaviors include absorption, reflection, diffraction, and refraction.

10

Sound reflection



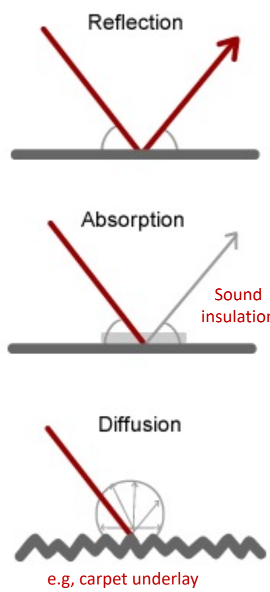
- A **reflection** occurs when a wave strikes an object or surface and bounces off.
  - An echo is reflected sound.
  - Echoes bounce off the walls, floor, ceiling, furniture, and people.
- A hard, smooth surface (cardboard) reflects sound better than an uneven, soft surface (pillow). This is because the soft surface **absorbs** most of the sound

11

11

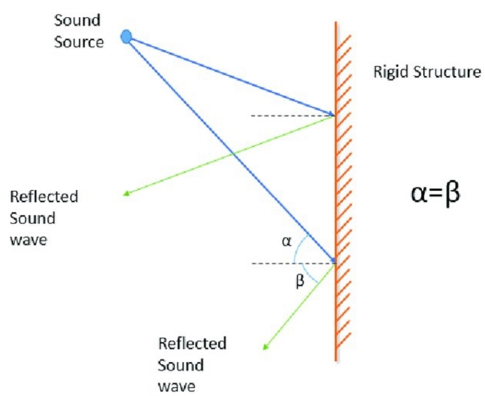
Sound reflection

- **Reflection:**
  - Sound is bounced off a surface, usually occurs on flat, rigid surfaces with a lot of mass like concrete or brick walls. Since the wave can't penetrate very far into the surface, it is turned back on itself like a ricochet.
- **Absorption**
  - When a sound wave hits particular surfaces (e.g. foam, rubber), the kinetic energy driving it is converted into a small amount of heat energy which dissipates, leeching power from the sound wave and causing it to decaying faster.
- **Diffusion**
  - When a sound wave hits an irregular surface like foam or carpet, the vibration breaks up and travels along many much smaller paths. This divides the energy of the wave, sending it in many different directions which depletes its energy faster.



12

Law of sound reflection

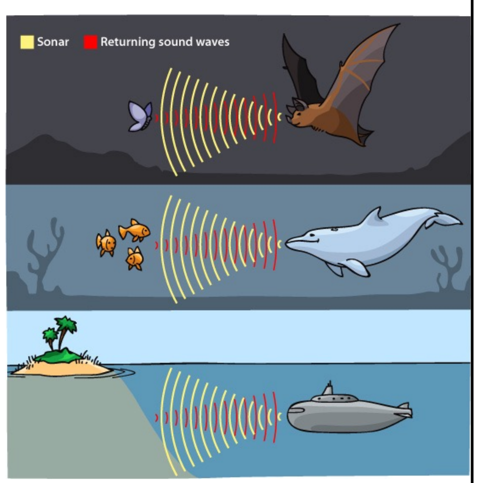


Law of sound reflection (similar to light)**:**

The angle of incidence of a sound wave equals the angle of reflection

Echo

- The sound heard after reflections from a rigid is called **echo.**
- It creates a persisting sound even after the sound source stopped vibrating.
- Echoes are used by bats and dolphins to navigate in their environment
  - Echolocation
- The same principle is used in SONAR (Sound Navigation And Ranging technique) for detection and localization of unseen underwater objects (submerged submarine, sunken ships and ice-bergs).



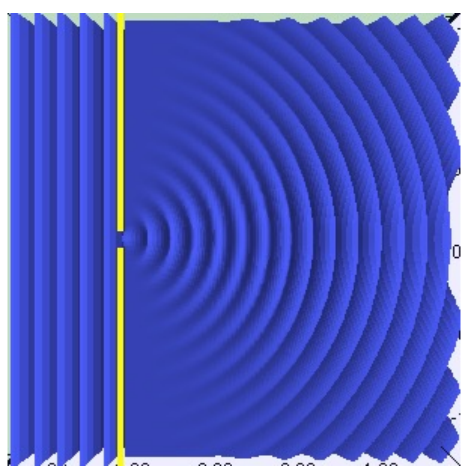
Echo

- Both SONAR and RADAR use the principle of reflection.
  - SONAR sends sound waves (generally in water)
  - RADAR send electromagnetic waves (in air)
  - SODAR (less used) which sends chirping sounds to detect wind speed and atmospheric temperature
- The technology records the time it takes for the reflections to arrive back.
- Stealth devices are those which attempt to make an object non-reflective – if the waves do not bounce off your aircraft, then no-one will know it is there!

15

Sound diffraction

- Diffraction is the bending of waves around a barrier (corners, door openings).
  - Owls are able to communicate across long distances due to the fact that their long-wavelength hoots can diffract around forest trees and carry farther than the short-wavelength tweets of songbirds.

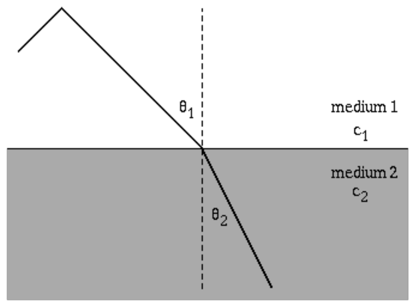


16

16

Sound refraction

- Refraction is the bending of a wave as it moves from one medium into another
  - The speed and wavelength of a wave changes during refraction.



Refraction law of sound waves (Snell's law):

$$\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_2}{c_2}$$

c_1, c_2: wave velocity in material 1 and 2

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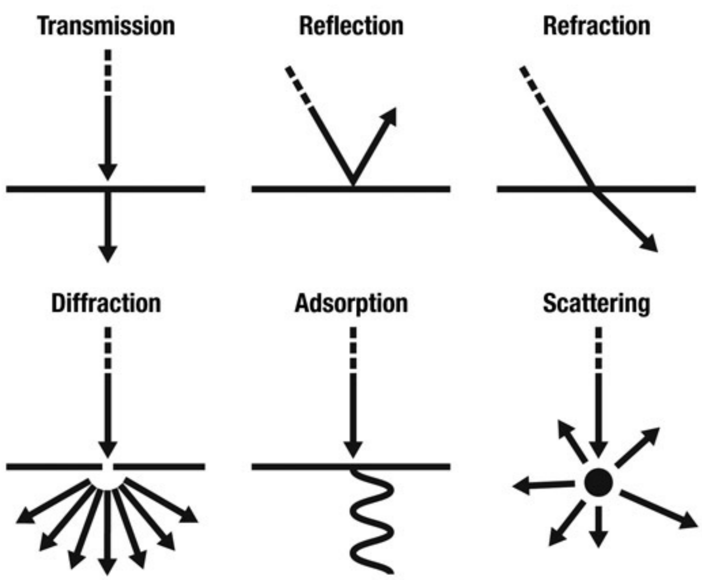
The ratio of wave angles is constant

17

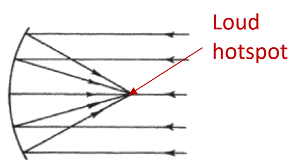
Sound wave –overview-



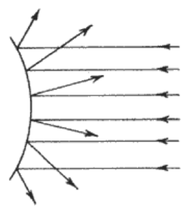
18

Sound proofing

- Room geometry will affect sound wave propagation
  - Parallel rooms cause flutter echo (when sound rapidly reflects back and forth between two acoustically reflective, parallel surfaces)
  - Even a 10degree angle can help sound dispersion
- Sound absorbers are often used in concert halls (usually ceilings and back walls) to stop the sound from reflecting
- Concave vs. convex surfaces



cause sound reflections to converge at a focal point at the geometric center of the curve

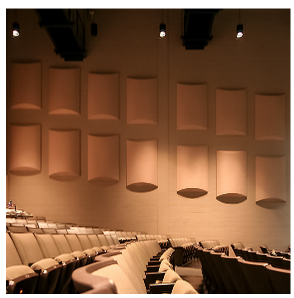


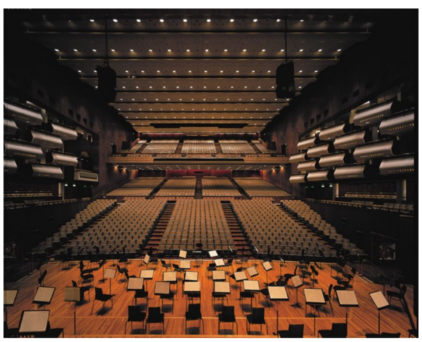
diffuse or reflect sound in many directions

19

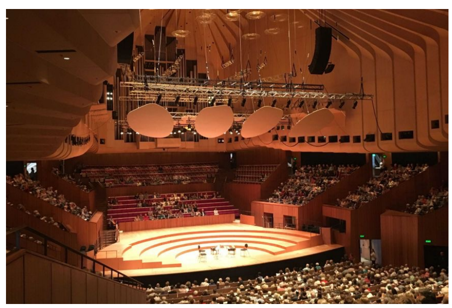
19

Sound proofing





Royal festival hall, London



Sydney opera house

20

20

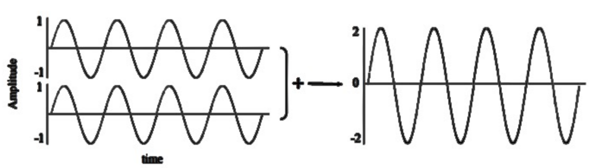
Wave interference

- When sound waves bounce off obstacles, they interfere with each other
- Tends to reinforce some frequencies and attenuate others

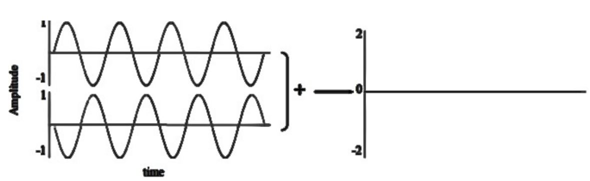
21

Wave interference

In phase:
cycles coincide exactly (sum duplicates amplitude)



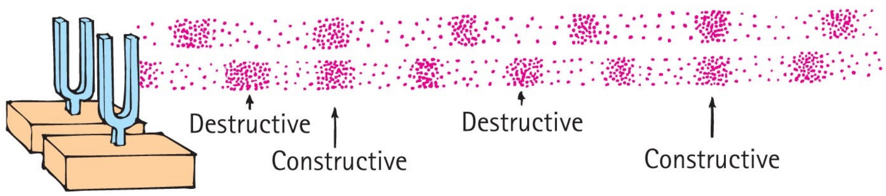
Out of phase:
half cycles are exactly opposed (sum cancels them)



22

Beats

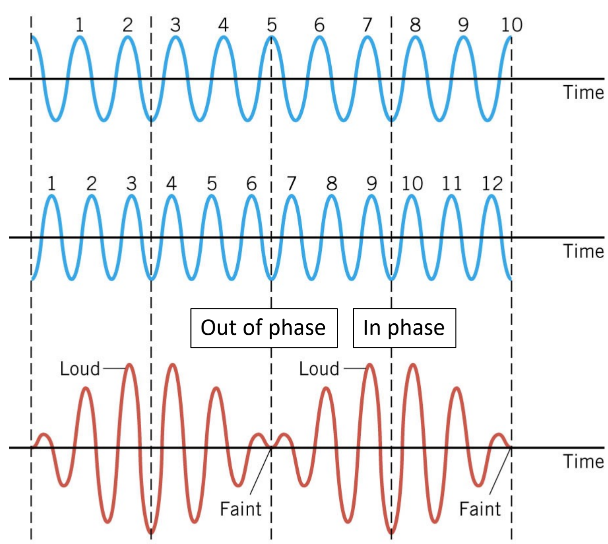
- Beats are periodic variations in the sound wave due to interference



23

23

Beats



The beat frequency is:
$\Delta f = f_1 - f_2$

24

24

Beats

- Beats are used in musical tuning:
  - Piano tuning by listening to the disappearance of beats from a tuning fork and a piano key
  - Tuning instruments in an orchestra by listening for beats between instruments and piano tone

25

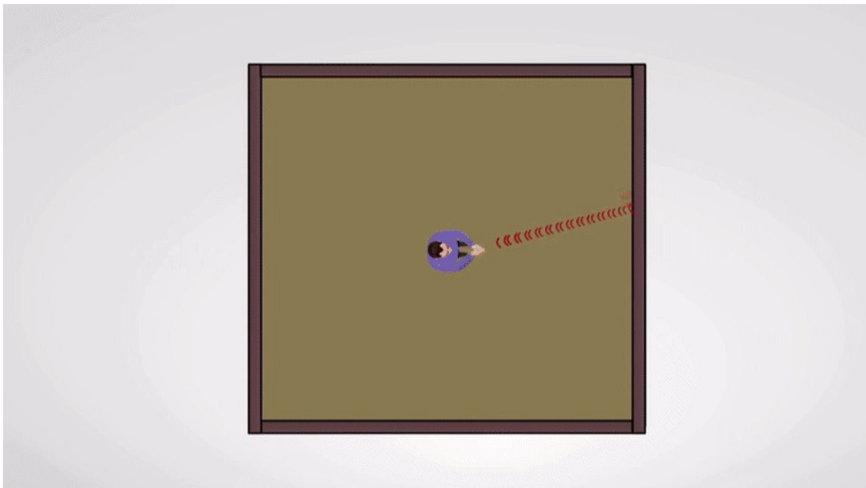
25

REVERBERATION

26

26

Reverberation



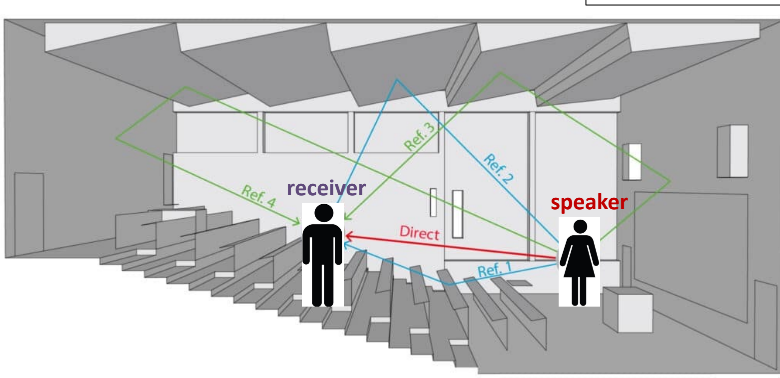
27

27

Reverberation

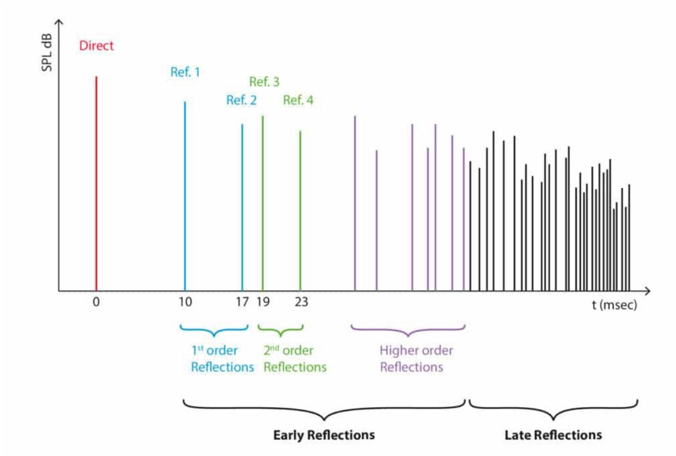
- Multiple, blended sound images caused by reflections from walls, ceilings and other structures which do not absorb sound

Sum of all reflections is called reverberation



28

Reverberation



Splitting point somewhat arbitrary

29

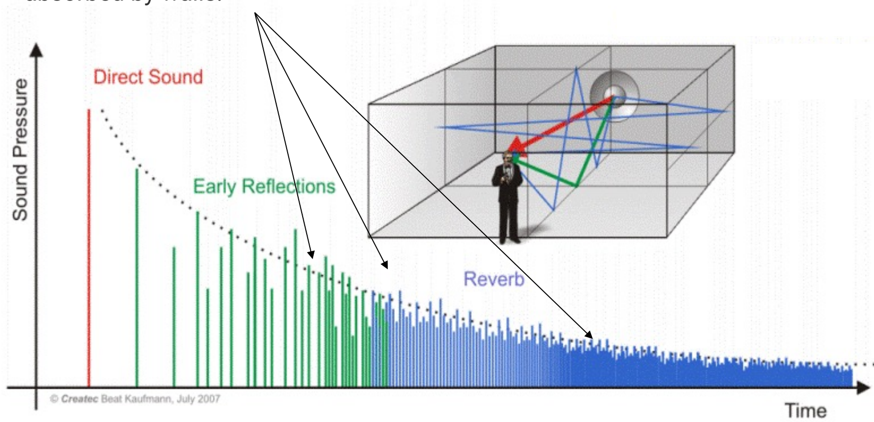
29

Reverberation

At every reflection, part of the sound is absorbed from the wall and loses energy. This continues until initial sound is fully absorbed by walls.

Extreme cases (unrealistic)

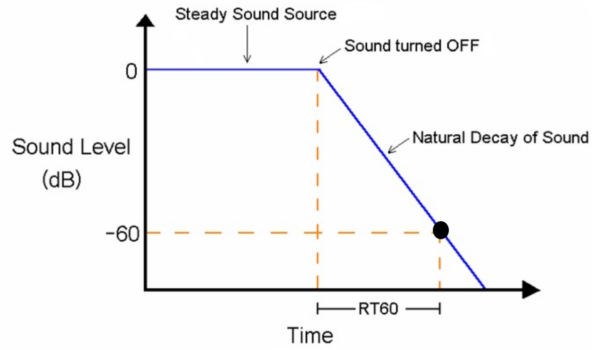
- A wall that does not absorb any energy is called a rigid wall
- A wall that absorbs all the energy is called a soft wall



30

Reverberation time constant

- Reverb time T_{60} is the time required for the level of a steady sound to decay by a certain amount (60 dB) after the sound has stopped



original

2sec reverb

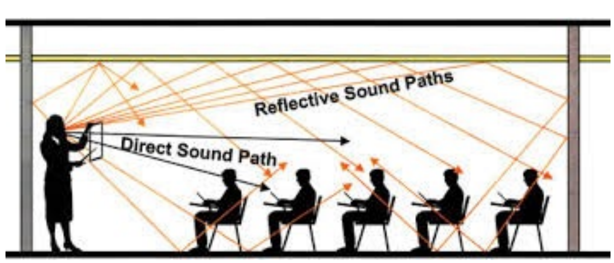
5sec reverb

31

31

Reverberation (Reverb)

- Reverberation is
  - desirable property of auditoriums
  - helps overcome drop-off of sound intensity in enclosure, but at <u>right amount</u>

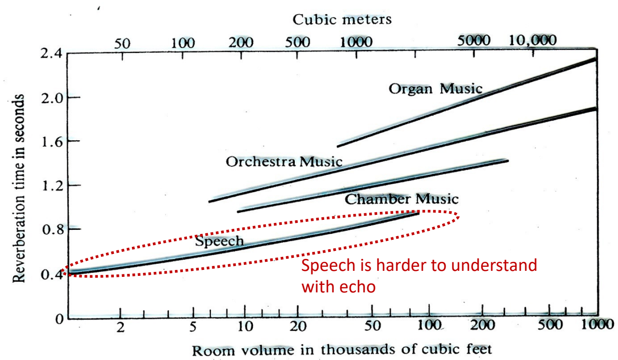


32

Absorption

- Controlling reflections can reduce or increase reverb time
- Specialists are often hired to "tune" a space acoustically

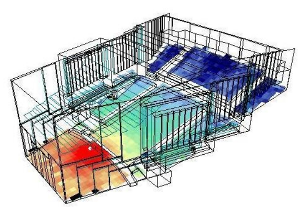
Desirable reverberation times for different sizes and functions

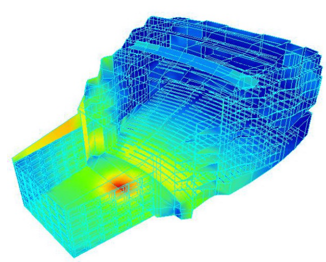


33

Room acoustics properties

- Intimacy
  - ✓ Related to size of a room (how it sounds to the listener, not actual size)
  - ✓ Determined by Interval between sound that arrives directly at the ear and the first reflection (initial-time-delay-gap – ITDG)
- Liveness
  - ✓ Related to Reverberation and size of the room
  - ✓ More reflection is live. Less reflection is dry or dead
- Warmth
  - ✓ Low frequency relative to mid frequency (too much low frequency sound is said to be "Boomy")

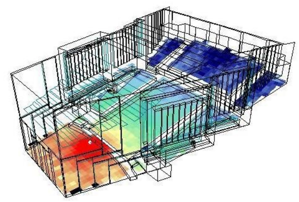


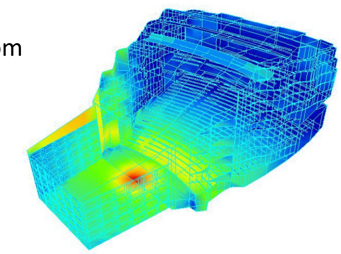


34

Room acoustics properties

- Loudness of direct sound
  - ✓ Loudness of sound will decrease by one ¼ every time the distance from the source is doubled
- Diffusion
  - ✓ Relates to the orientation of reverberant sound
    - where is the reflected sound coming from
  - ✓ It is preferable to have reverb sound coming from all directions
- Other attributes:
  - ✓ Definition (sound should be clear)
  - ✓ Clarity
  - ✓ Brilliance





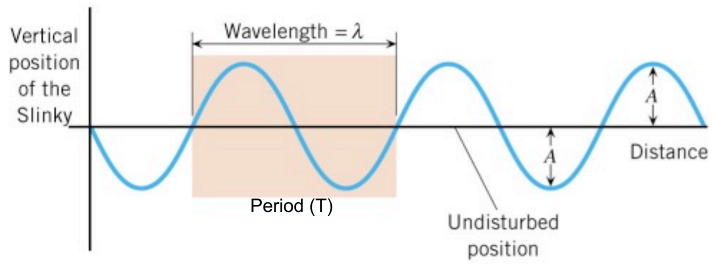
35

Physical Dimensions of Sound

36

36

Physical Dimensions of Sound



Amplitude
- Height of a cycle

Frequency (F)
- Cycles per second

Wavelength (λ)
- Distance traveled by one cycle

37

37

PHYSICAL DIMENSION: AMPLITUDE

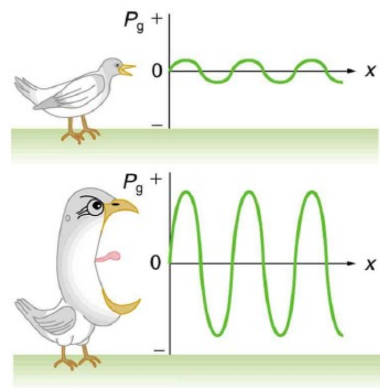
38

38

Physical Dimensions: Amplitude

- Amplitude is the measurement of degree of change (positive or negative) in atmospheric pressure caused by sound waves.
  - measured in *amount of force applied over an area*.
    - Sound requires energy (pushing atoms/molecules through a distance)
  - Sound pressure is measured in units of Pascals
  - 1 Pascal (Pa) = 1 Newton of force/m^2
  - Human absolute hearing threshold = 0.00002 Pa = 20 microPa

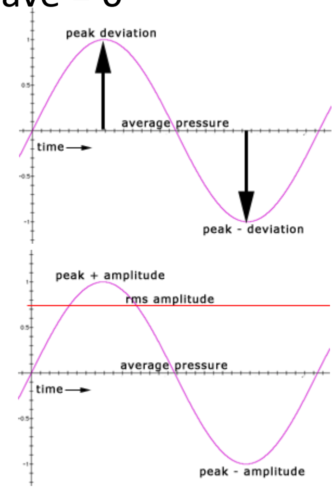
(1 KHz note)



39

Measuring amplitude

- Average amplitude of a sine wave = 0
- Alternatives:
  - Peak-to-peak amplitude
  - Root-mean-squared (RMS):
    - Average of amplitude squared



40

Sound intensity

- Sound Intensity
  - Related to energy/power in the signal and area of travel
    - A high amplitude wave carries a large amount of energy; a low amplitude wave carries a small amount of energy
    - Intensity takes into account space and time:
      - Even if you have a powerful sound source (loud speaker), intensity will be small far away
  - *Intensity = rate of energy flow over an area*

$$\boldsymbol{I = \frac{Power}{Area} = \frac{Energy/_{Time}}{Area}} \qquad \left(Watts/_{Meter^2}\right)$$

  - Intensity is related to how <u>loud</u> we perceive the sound

41

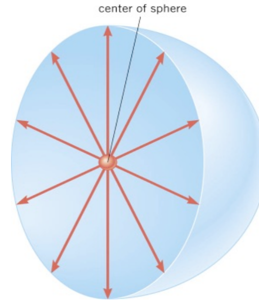
41

Intensity and distance

- Why does sound get fainter further away from a source?
  - Sound from a point produces a spherical wave
  - The amount of energy passing through a spherical surface is the same but the area gets larger further away from the source

$$I = \frac{Power}{Area} = \frac{Power}{4\pi r^2}$$

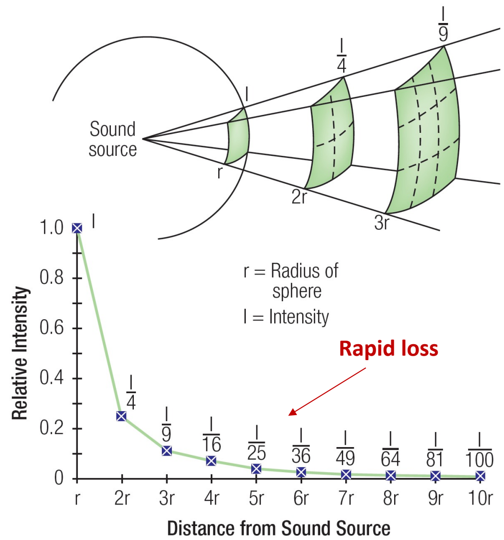
Area of sphere



42

42

Inverse square Law



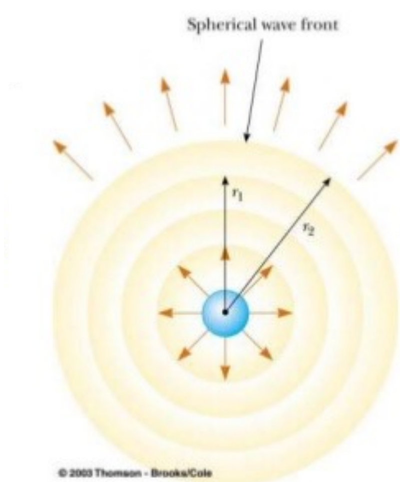
$$I = \frac{Power}{Area} = \frac{Power}{4\pi r^2}$$

$r = 1$	$I = {}^{P}/_{4\pi}$	I
$r = 2$	$I = {}^{P}/_{16\pi}$	$\frac{I}{4}$
$r = 3$	$I = {}^{P}/_{36\pi}$	$\frac{I}{9}$

* Assumes no reflections/reverberation

43

Inverse square Law



- Moving around a point of constant distance from source produces no change in intensity (or 'loudness')
- Though the power of sound remains the same, the area covered becomes bigger as you move away from source; hence intensity decreases

44

Intensity

- Pressure variations displace membrane (eardrum, microphone) which can be used to measure sound
  - Typical speaking voice moves eardrum by a mere 1.5×10^{-4} mm = 150 nm = 1/4 wavelength of visible light!
  - threshold of hearing detects 5×10^{-8} mm motion, one-half the diameter of a single atom!!!
  - pain threshold corresponds to 0.05 mm displacement

- Smallest change in loudness that an average listener with normal hearing can detect is about one-decibel (1-dB)
  - Called JND: Just noticeable difference

45

45

Intensity in Decibels – Sound Pressure Level (SPL)

- Recall:
  - Human absolute hearing threshold

Reference Sound pressure

$$P_0 = 0.00002\ (Pa) = 20\ (\mu Pa)$$
$$I_0 = 10 \text{ x } 10^{-12}\ (W/m^2)$$

Reference Sound intensity

- Alternative measure of sound pressure level:

$$\boxed{L = 10log_{10}\frac{I}{I_0}}$$

Relative measure (intensity of sound relative to reference threshold)

Units:
Decibels (dB) or dB (SPL)

46

46

Sound Pressure Level

- Decibel is a (unit-less) quantity that represents the log-ratio between a measured value and a reference value.
- Sound measurements can be:
  - **P:** Pressure (Pa) — **Amplitude** measure (e.g. voltage)
  - **W:** Power (Watts), or **I:** Intensity (W/m^2) — **Power** measures (e.g. electrical power)

$$\boxed{L = 10log_{10}\left(\frac{P}{P_0}\right)^2}$$

$$\boxed{L = 10log_{10}\left(\frac{I}{I_0}\right)}$$

47

47

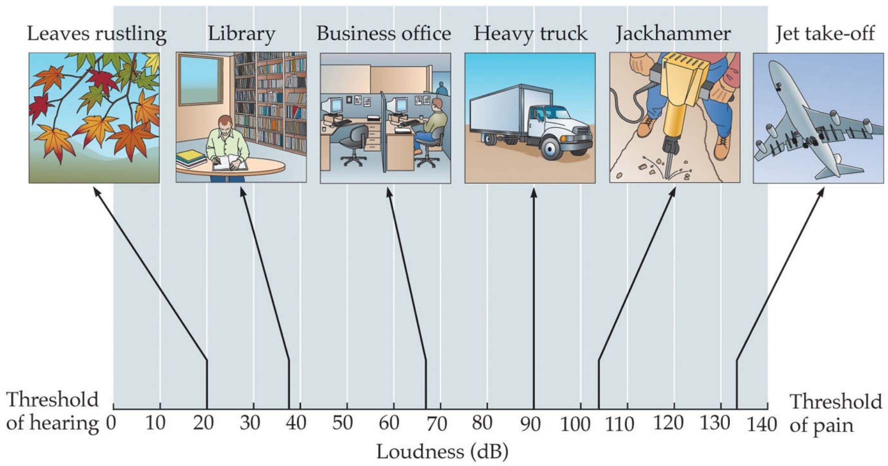
Sound Pressure Level (SPL)

- Decibels:
  - Deci: factor of 10
  - Bels: after Alexander Graham Bell
- What does 0dB refer to?
  - <u>Hint</u>: $10\ log_{10}\left(\frac{20\mu Pa}{20\mu Pa}\right)^2$ = 0 dB
- Decibels provide a **relative** measure of sound intensity.
- The unit is based on powers of 10 to give a manageable range of numbers

48

48

Sounds in the environment

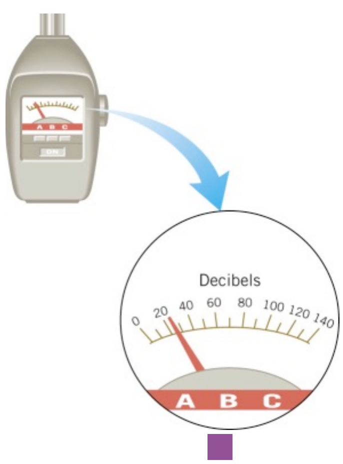


Note: Listening to loud music will gradually damage your hearing!

49

49

Sound Pressure level can be measured with a sound meter



	Intensity I (W/m^2)	Sound Level (dB)
Threshold of hearing	1.0×10^{-12}	0
Rustling leaves	1.0×10^{-11}	10
Whisper	1.0×10^{-10}	20
Normal conversation (1 meter)	1.0×10^{-6}	65
Inside car in city traffic	1.0×10^{-4}	80
Car without muffler	1.0×10^{-2}	100
Live rock concert	1.0	120
Threshold of pain	10	130

50

50

Doubling sound intensity

- Doubling the intensity adds 3 decibels to SPL
- Assume system 1 produces sound at 70dB

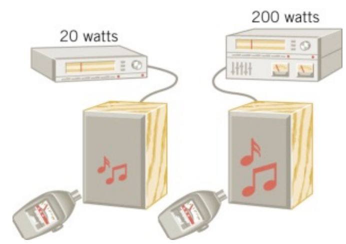
  and system 2 produces sound at 73dB

  what is ratio of I_1/I_2?

$$3 = L_2 - L_1 = 10\log\frac{I_2}{I_0} - 10\log\frac{I_1}{I_0}$$

$$= \quad 10\log\frac{I_2}{I_1}$$

$$\frac{I_2}{I_1} \quad = \quad 10^{0.3} \quad \simeq \quad 2$$



51

Intensity from Multiple Sources

- **Intensity** is additive. **SPL** (in dB) is not additive
- Use energy combination equation

$$L = 10\log(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + \ldots + 10^{\frac{L_N}{10}})$$

where L_1, L_2, …, L_n are in dB

52

52

Example

- If one machine emits 80 dB_{SPL} then how much sound pressure level would be expected from two machines side-by-side?
  - 2 x 80 = 160 dB_{SPL} ??? (That's pretty intense)
  - Convert from dB_{SPL} back to sound intensities, sum the intensities, then convert sum to dB_{SPL}
    $\approx$ 83dB SPL
    - which is adding the 3dB-SPL expected from doubling the intensity

53

53

US OSHA [Occupational safety & Health admin] Guidelines

Max duration	**SPL**	**Example source**
8 hours	90 dBA	Lounge duo
6	92	
4	95	Subway train
3	97	
2	100	Very loud orchestra
1.5	102	
1	105	Roomate screaming at close range
0.5	110	
< 0.25	115	Loudest parts at a rock concert

dBA is slightly different than dB-SPL:
it refers to A-weighted dB which accounts for nonlinear behavior of human ear (discussed next)

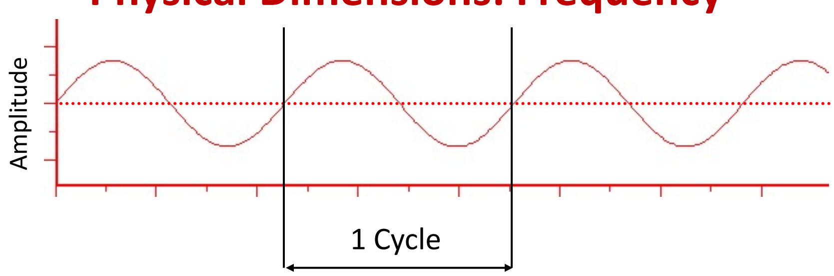
54

PHYSICAL DIMENSION: FREQUENCY

55

55

Physical Dimensions: Frequency

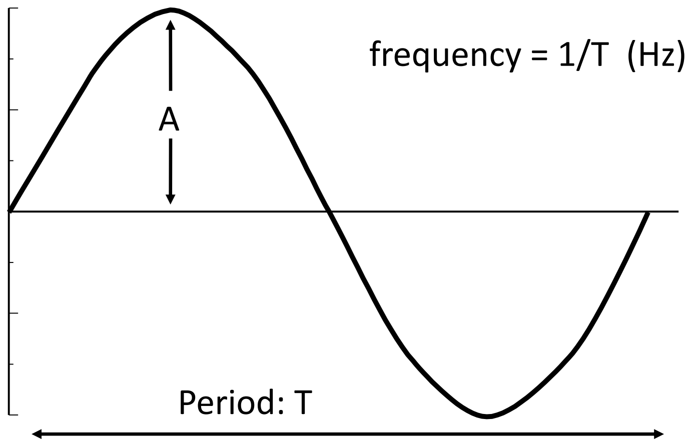


- Cycle:
  - single push and pull of the vibrating object
  - An initial increase in atmospheric pressure from the norm, followed by a drop below the norm and then a return to normal
- Period (T) and Frequency (f)
  - Period - The time it takes to create one cycle
  - Frequency - The number of cycles in one second
    - Measured in Hertz (Hz) or cycles per second

$$f = \frac{1}{T}$$

56

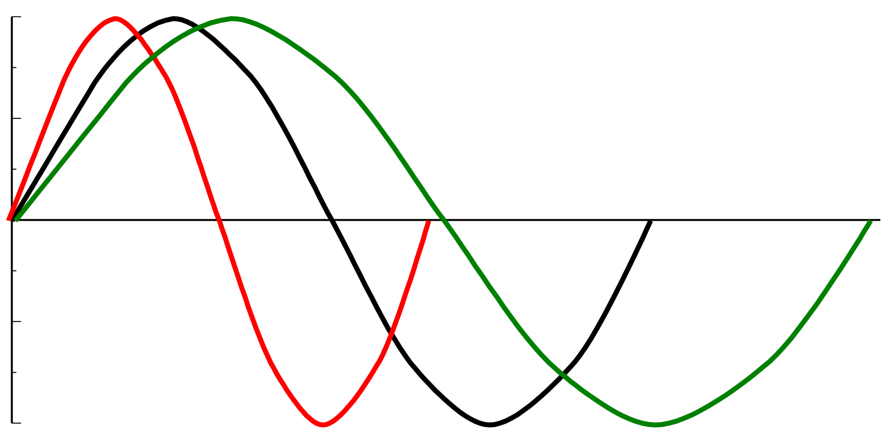
The simplest sound waves - ***Pure Tones***



57

57

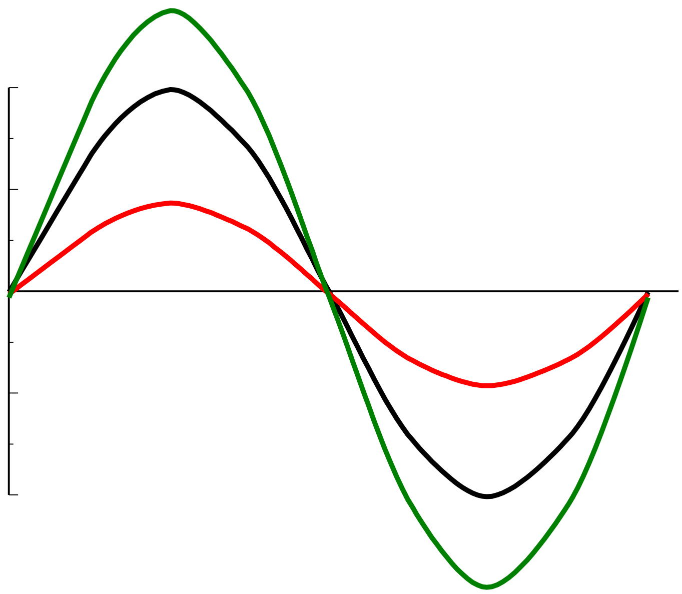
Pure tones can vary in frequency.....



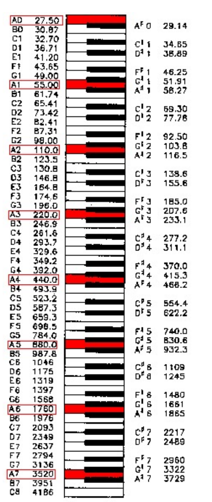
58

58

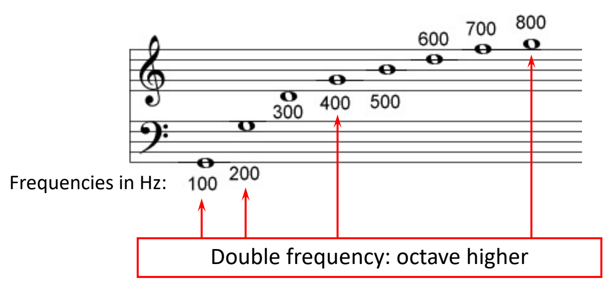
or amplitude.



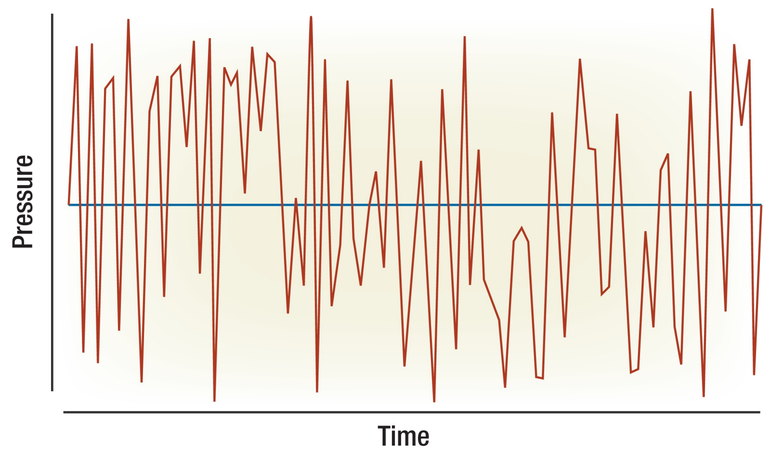
Frequency



- An <u>octave</u> is twice the frequency [power of 2]
- E.g.
  - A5 (880Hz) is an octave above A4 (440Hz)
  - A4 (440Hz) = A1 (55Hz) x 2^3



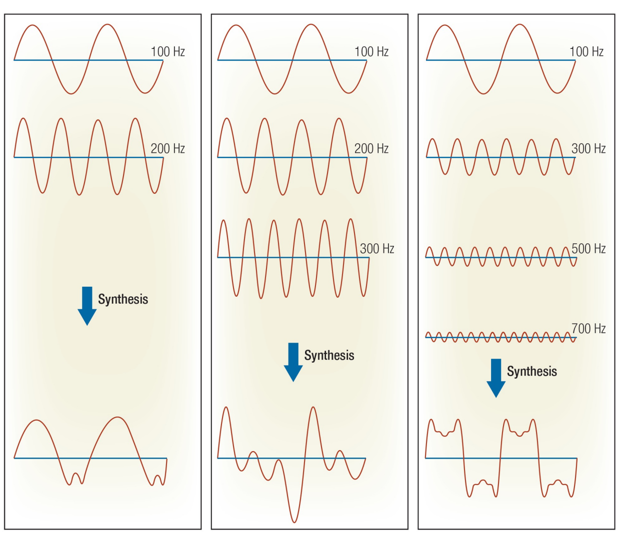
Most sounds are complex (not simple tones)



61

61

Complex Sound = Sum of Sines (Fourier Theorem)



J.B.J. Fourier
(1768-1830)

62

Frequency

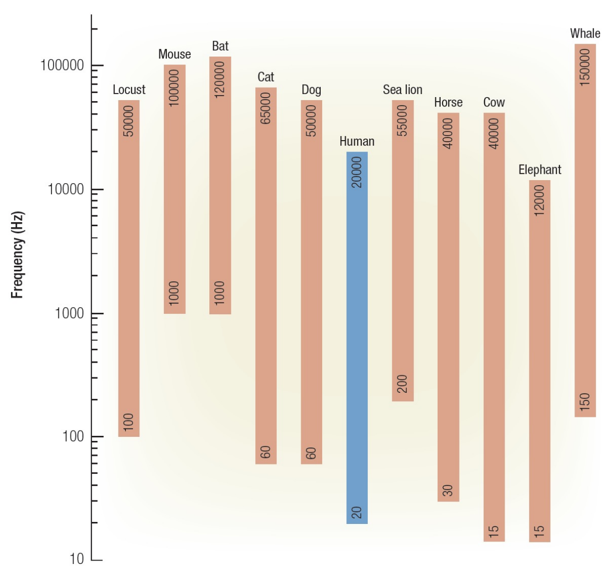
- Sound waves with frequencies below 20 Hz are said to be *infrasonic,* while those with frequencies above 20 kHz are referred to as *ultrasonic.*
- Rhinoceroses use infrasonic frequencies as low as 5 Hz to call one another, while bats use ultrasonic frequencies up to 100 kHz for locating their food sources and navigating.
- The human brain can hear between 20Hz and 20KHz (reduced with age)

40 Hz 800 Hz 2000 Hz 8000 Hz 15000 Hz 19000 Hz

63

63

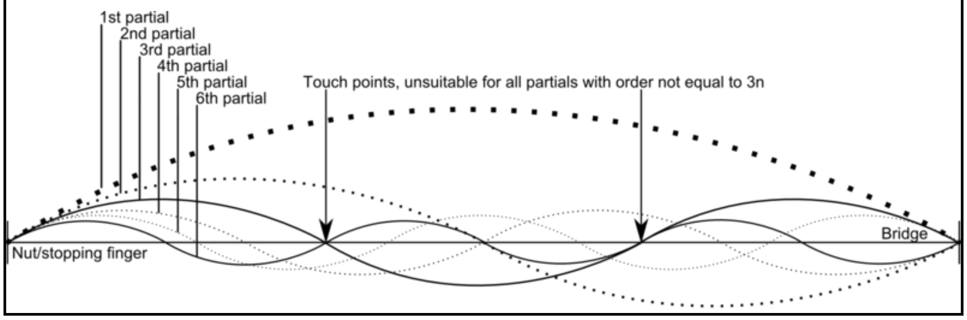
Species-Specific Frequency Range



64

Harmonics

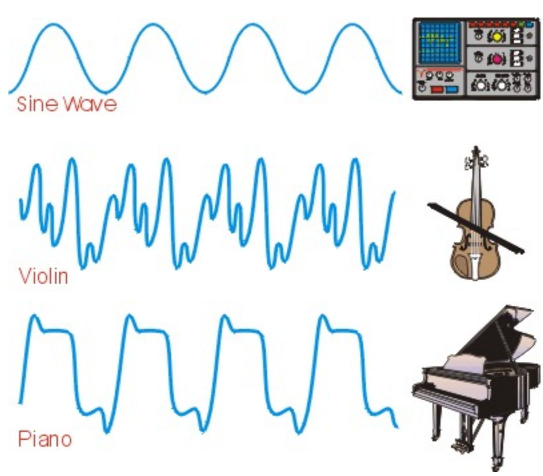
- Most vibrating sources do not just vibrate at one frequency
  - Vibration inside a tube forms a standing wave.
    - Wave reflects off end of tube (open or closed) and interferes with itself.
    - Waves that don't fit in tube are lost
  - Longest wave that fits in tube is fundamental F_0
  - Other waves that fit are overtones (partials/harmonics); i.e. $kF_0, k \in \mathbb{N}$



65

Harmonics/Overtones

- Different instruments generate different overtones
- The overtones combine to form the characteristic sound of the instrument
  - For example, all waves in figure play same note (same fundamental frequency) but their overtones are different, and therefore their sounds are different



66

PHYSICAL DIMENSION: WAVELENGTH

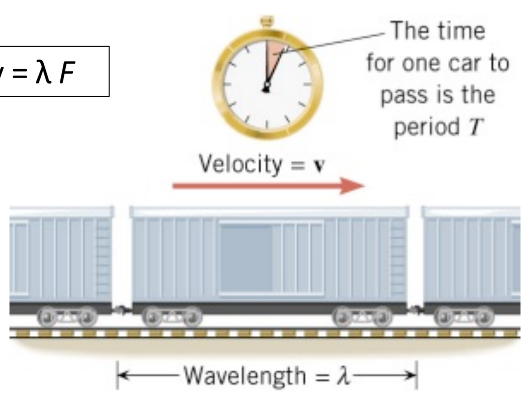
67

67

Physical Dimensions: Wavelength

- Wavelength is the distance over which one wave cycle repeats
- It is measured in meters (m)
- Relationship between period (T), velocity (v) and wavelength (λ):

$$\boxed{\text{velocity} = \lambda\, F}$$

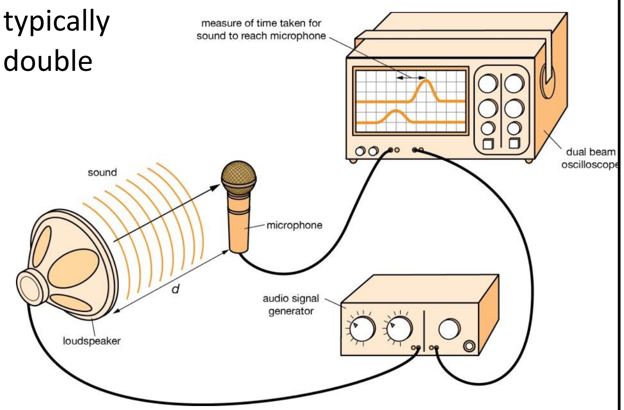


68

68

Speed of sound

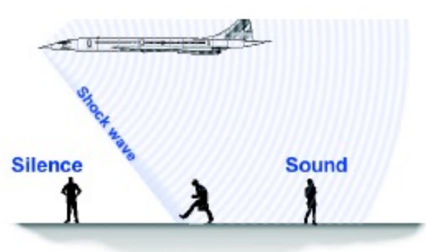
- Speed of sound in the air is ~ 340 m/s (742 MPH) at ambient temperature (~20◦ C)
- This velocity changes depending on medium and temperature.
- Speed of sound is typically measured using a double beam oscillator



69

Speed of sound

- An object is subsonic when it is moving <u>slower</u> than sound.
- We use the term supersonic to describe motion at speeds <u>faster</u> than the speed of sound.

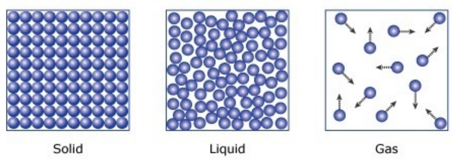


70

Effect of medium

- Sound velocity changes very much in different media.
  - It travels faster in non-porous solids than in air (molecules in solids are closer together)
  - It is the "compression" that travels not the medium, *per se*.

Medium	Sound Speed (metres/second)
Gas	
Carbon dioxide	268
Air	331
Helium	972
Liquid	
Ethanol	1,130
Fresh water	1,402
Sea water	1,522
Solid	
Brass	4,700
Steel	5,790
Aluminum	6,420



* Slightly colder than ambient temperature (20◦)

Effect of temperature

- The temperature of the material affects the speed of the sound.
- Molecules move faster in *warmer* substances. As a substance heats up, its molecules move faster, so they collide more frequently
  - Sound travels faster in warmer temperatures. The more frequent the collisions are, the faster the speed of sound is in the material.