$\frac{\partial p}{\partial x} = -p_0 \frac{\partial u}{\partial t}$	linearized Euler equation
$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$	1d lossless wave equation
$p(x,t) = F(x \pm ct)$	General solution to 1d wave equation
$p(x,t) = Acos(\omega t - kx)$	Time harmonic solution to 1d lossless wave eq
$k = \frac{\omega}{c}$	Wave number (rad/m)
$2\pi f = \omega$	Frequency (Hz, s^-1)
$\lambda = \frac{c}{f}$	Wave length (m)
$\underline{P}(x,t) = \lvert\underline{A}\rvert e^{j(\omega t - kx + \varphi_A)}$	Complex notation for plane wave
$\underline{Z_A} = \frac{\underline{p}}{\underline{u}}$	Specific acoustic impedance, general form (Rayls, Pa*m^-1*s)
$\underline{Z_A} = \frac{\underline{p}(x,t)}{\underline{u}(x,t)} = \rho_0 c$	Acoustic impedance for a plane wave that propagates in the +x direction Z0 is characteristic impedance
$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$	Spherical wave equation
$p(r,t) = \frac{A}{r}\cos(\omega t - kr)$	Time-harmonic solution to the 3D wave equation
$\underline{Z_A} = \rho_0 c \frac{kr}{\sqrt{1+(kr)^2}}$	Specific impedance for spherical wave (real part)
$P_{RMS} = \sqrt{\frac{1}{T}\int_0^T p(t)^2 dt}$	Definition of RMS as applied to Pressure
$P_{RMS} = \frac{A}{\sqrt{2}}$	For time-harmonic pressure wave
$\vec{I} = p(x,t)\vec{u}(x,t)$	Acoustic intensity (Power/area)
$I_{avg} = \frac{P_{RMS^2}}{\rho_0 c} = \frac{\lvert\underline{p}\rvert^2}{2\rho_0 c}$	Time-averaged acoustic intensity For plane wave in +x direction
$W = SI$	Acoustic power (S is reference area) (Watts)
$W = 4\pi r^2 I$	Acoustic power for spherical wave
$D = \frac{\lvert\underline{p}\rvert^2}{\rho_0 c^2} = \frac{I_{avg}}{c}$	Energy density for a plane wave
$D = \frac{\lvert\underline{p}\rvert^2}{\rho_0 c^2}\left(1 + \frac{1}{2k^2 r^2}\right)$	Energy density for spherical wave
$L_p = 20\log\left(\frac{P_{RMS}}{P_{ref}}\right) = 10\log\left(\frac{P_{RMS^2}}{P_{ref^2}}\right)$	Sound pressure level (decibels) P_ref = 20 micro-Pa
$P_{RMS} = P_{ref} * 10^{\frac{L_p}{20}}$	P_rms in terms of Lp and Pref

$L_w = 10log\left(\frac{W}{W_{ref}}\right)$	Sound power level Wref = 10^-12 Watts	
$L_I = 10log\left(\frac{I}{I_{ref}}\right)$	Sound intensity level I ref =10^-12 Watts/m^2	
$L_{p,tot} = 10log\left[10^{\frac{L_{p1}}{10}} + 10^{\frac{L_{p2}}{10}}\right]$	Total sound pressure level if sources incoherent	
$L_p(r) = L_{w,src} - 20\log\left(\frac{r}{r_0}\right) - 10.9dB$	Sound pressure level in air in reference to distance from a source, r0 = 1m	
$L_p = L_w + DI - 20log\left(\frac{r}{r_0}\right) - 10.9dB$	DI = directivity index 10log(Q) Q = directivity	DI = 3dB, wall DI = 6dB, 2 walls DI = 9dB 3 walls
$L_p(r2) = L_p(r1) + 20log\left(\frac{r1}{r2}\right)$	Sound pressure level at a distance r2 w.r.t r1	
$\underline{R} = \frac{p_r}{p_i} = \frac{1 - \frac{z_1}{z_2}}{1 + \frac{z_1}{z_2}}$	Pressure reflection coefficient for normal incident waves	
$\underline{T} = \frac{p_t}{p_i} = \frac{2\frac{z_2}{z_1}}{1 + \frac{z_2}{z_1}}$	Pressure transmission coefficient for normal incident waves	
$a_r = \frac{W_r}{W_i} = \left(\frac{z_2 - z_1}{z_1 + z_2}\right)^2$	Power reflection coefficient, should be between 0 and 1	
$a_t = \frac{W_t}{W_i} = \frac{4z_1z_2}{(z_1 + z_2)^2}$	Power transmission coefficient, should be between 0 and 1.	
$a_t + a_r = 1$	Due to the conservation of energy	
$TL = 10\log\left(\frac{1}{a_t}\right)$	Transmission Loss	
$L_{Pt} = L_{Pi} - TL + 10\log\left(\frac{z_2}{z_1}\right)$	Acoustic pressure level of the transmitted wave in terms of the transmission level (cannot write L_pt = L_pi – TL	
$\frac{sin\theta_i}{c_1} = \frac{sin\theta_t}{c_2}$	Snell's law – applies to oblique incidence	
$\underline{R} = \frac{\frac{cos\theta_i}{z_1} - \frac{cos\theta_t}{z_2}}{\frac{cos\theta_i}{z_1} + \frac{cos\theta_t}{z_2}}$	Pressure Reflection coefficient for oblique transmission	
$\underline{T} = \frac{2z_2cos\theta_i}{z_2cos\theta_i + z_1cos\theta_t}$	Pressure Transmission coefficient for oblique transmission	
$a_t = \frac{4z_1z_2cos\theta_icos\theta_t}{(z_1cos\theta_t + z_2cos\theta_i)^2}$	Sound power transmission coefficient for oblique transmission	
$\theta_{CR} = arcsin\left(\frac{c_1}{c_2}\right)$	Critical angle. If theta_i > theta_cr, no energy is transmitted in medium 2	

$a_t = \dfrac{4}{4\cos^2(k_2L) + \left(\frac{z_1}{z_2} + \frac{z_2}{z_1}\right)^2 sin^2(k_2L)}$	Transmission through walls if z_1 and z_3 are identical
$TL_{\,n,region\ I} = 10\log\left[1 + \dfrac{1}{k_s(\omega)^2}\right]$	Transmission loss for Region I: stiffness-controlled zone (normal incidence) $k_s(\omega) = 2\omega\rho c C_s\ (normalised\ compliance)$
$TL_{\,region\ I} = -20\log(K_s) - 10\log[0.23026 * TL_n]$	Transmission loss for Region I: stiffness-controlled zone (including random incidence)
$C_s = \dfrac{768(1-\sigma^2)}{\pi^8 E h^3 \left(\frac{1}{a^2} + \frac{1}{b^2}\right)^2}$	Compliance (property of the wall material) E = Young's modulus, sigma is Poisson's ratio
$f_n = \dfrac{\pi}{4\sqrt{3}} C_L h \left[\dfrac{1}{a^2} + \dfrac{1}{b^2}\right]$	Frequency of resonance, occurs between Region I and Region II. C_L longitudinal wave speed in plate material
$TL_{n,region\ II} = 10\log_{10}\left(1 + \left(\dfrac{\pi M_s f}{\rho_1 c_1}\right)^2\right) - 5dB$	Transmission loss in Region II (Mass-controlled). M_s = rho*w*h (h is the wall thickness)
$TL_{\,region\ II} = TL_n - 5dB$	Transmission loss in Region II with random inc.
$f_c = \dfrac{\sqrt{3}c_1^2}{\pi C_L h}$	Frequency of coincidence, occurs between Region II and Region III (CL is longitudinal wave speed in plate material)
$TL_{\,region\ III} = TL_n(f_c) + 10\log_{10}\eta + 33.22\log_{10}\left(\dfrac{f}{f_c}\right) - 5.7dB$	Transmission loss for Region III (Purely empirical) Eta = "loss factor" of material
$a_t = \dfrac{1}{S_{tot}}(S_1 a_{t1} + S_2 a_{t2})$	Power transmission coefficient in a composite wall (weighted average)
$a_t = \dfrac{4\nu}{(1+\nu)^2\cos(kL) + \left(m + \frac{\nu}{m}\right)^2 \sin^2(kL)}$	Power transmission coeff if z1=z2=z3 but the area is changing Nu = S3/S1 and m = S2/S1
$a_t = \dfrac{4}{4 + \left(m - \frac{1}{m}\right)^2 \sin^2(kL)}$	Power transmission coeff for area changing chamber if S1 = S3
$L_p(x) = L_p(0) - 8.6859\alpha x$	Acoustic pressure level with attenuation for Plane Wave; Alpha*x units are called Neper (Np)
$L_p(r) = L_w(r_0) - 8.6859\alpha(r - r_0) - 20\log_{10}\left(\dfrac{r}{r_0}\right) - 10.9dB$	Acoustic pressure level with attenuation for Spherical wave
$\alpha = \alpha_{classical} + \sum_i \alpha_{vi}$	Attenuation coefficient
$\alpha_{classical} = \dfrac{2\pi f^2 \mu}{\rho_0 c^3}\left[\dfrac{4}{3} + \dfrac{(\gamma - 1)}{Pr}\right]$	Alpha due to viscothermal losses Mu = viscosity, gamma = ratio of spec. heats, Pr = Prandtl number, (mu*Cp/k) k = thermal conductivity, Cp is specific heat)
$\alpha_{vi} = \dfrac{\alpha_{\infty i}(\omega\tau_{vi})^2}{1 + (\omega\tau_{vi})^2}$	Attenuation due to molecular relaxation Alpha_inf = limiting upper bound Tau_vi = relaxation time constant

$\frac{1}{a_t} = C_1^2 \cos^2 kL + C_2^2 \sin^2 kL$	Inverse of the power transmission coefficient for a muffler with acoustic lining
$C_1 = \cosh(\sigma L) + \frac{1}{2}\left(m + \frac{1}{m}\right)\sinh(\sigma L)$ $C_2 = \sinh(\sigma L) + \frac{1}{2}\left(m + \frac{1}{m}\right)\cosh(\sigma L)$	C1 and C2 for the above equation, Sigma is the attenuation coefficient for the acoustic lining of the muffler (m^-1), m is the area ratio S2/S1, L is the length of the chamber
$f = \frac{c}{2}\sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2}$	Frequency of standing waves in a rectangular room of three dimensions
$M_A = \frac{\rho_0 L_e}{S}$	Acoustic mass (Helmholtz Resonator) (kg/m^4)
$L_e = \Delta L_1 + \Delta L_2 + L$	L = actual length of neck in resonator, delta_L = end corrections
$\Delta L_{open\ end} = 0.613a$	A is radius of neck
$\Delta L_{flanged\ end} = \frac{8a}{3\pi}$	Flanged end
$a = \sqrt{\frac{S}{\pi}}$	If neck is not circular, this is the effective radius, where S is the area
$C_A = \frac{V}{\rho_0 c^2}$	Acoustic compliance
$r_v = \frac{a}{\sqrt{\frac{\mu}{2\pi f \rho_0}}}$	Ratio of cross sectional dimensions to viscous boundary layer thickness
$R_A = \frac{8\mu L}{\pi a^4}$	Acoustic resistance if r_v < 4*sqrt(2)
$R_A = \frac{\sqrt{4\pi f \mu \rho_0}}{\rho_0 a^2}\left(\frac{L}{a} + 2\right)$	Acoustic resistance if r_v > 4*sqrt(2)
$\omega_0 = \sqrt{\frac{Sc^2}{L_e V}}$	Frequency of resonance for a Helmholtz Resonator
$Q_A = \frac{M_A \omega_0}{R_A}$	Quality factor for Helmholtz Resonator
$G = \frac{\frac{\omega}{\omega_0} Q_A}{\sqrt{1 + Q_A^2\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)^2}}$	Pressure Gain for Helmholtz Resonator (Gain evaluated at the resonance freq is Q_A)
$a_t = \frac{1 + Q_A\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)^2}{\left(\frac{\rho_0 c}{2SR_A}\right)^2 + Q_A^2\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)^2}$	Power transmission coefficient for a Side Branch Helmholtz Resonator

Outer Ear	Funnels sound waves into ear canal
Middle ear	Efficiently transmits sound from air-filled ear canal to water-filled cochlea
Cochlea	Converts pressure waves into electrical signals
Difference btwn cochlear response to high freq and low freq	High freq causes traveling wave that propagates towards basilar membrane w/ peak at or near it. Low freq. causes traveling wav that peaks at location closer to the other end of the cochlea (apex)
Inner hair cells	Sensory cells of cochlea (convert mechanical inputs into nerve impulse
Out hair cells	Amplifiers that boost the sound-evoke vibrations in response to low-level sounds
Range of human hearing	Around 20hz to 20 khz, about 0dB SPL to 100 dB SPL (after which is hearing loss)
Types of hearing loss	Conductive hearing loss due to abnormal middle-ear sound transmission
Sensorineural hearing loss	Due to problems w cochlea or brain
Methods for screening/ diagnosis of hearing loss	Air conduction audiometry, bone conduction audiometry, auditory brainstem response (ABR), otoacoustic emission (OAC) testing
$L_p = L_w + 10\log_{10}\left[\frac{4}{R} + \frac{Q}{4\pi r^2}\right] + 0.1dB$	Total sound pressure level
$R = \frac{\bar{\alpha}}{1-\bar{\alpha}} S_0$	Room constant
$\bar{\alpha} = \frac{\sum \alpha_i S_i}{S_0}$	Average surface absorption coefficient
$r^* = \sqrt{\frac{QR}{16\pi}}$	Critical distance
$T_{60} = \frac{55.26V}{ca}$	Reverberation time, the time it takes for SPL to decrease by 60 dB after an acoustic source stops
$a = S_0 ln\left(\frac{1}{1-\bar{\alpha}}\right)$	If all surfaces have the same alpha_i, use this equation for “a” in the above equation
$\frac{1}{a} = -\frac{1}{S_0}\left[\frac{S_x/S_0}{\ln(1-\bar{\alpha}_x)} + \frac{S_y/S_0}{\ln(1-\bar{\alpha}_y)} + \frac{S_z/S_0}{\ln(1-\bar{\alpha}_z)}\right]$	If surfaces have different alpha_i, use the Fitzroy equation here
$L_{p2} = L_w - 10\log_{10} R_1 + 10\log_{10}\left(\frac{4S_w}{R_2} + 1\right) - TL + 0.1\ dB$	NOISE FROM ANOTHER ROOM: If r_2 (distance from the wall to the receiver in the next room from the source) is greater than sqrt(Sw/2pi), the wall emits plane waves
$L_{p2} = L_w - 10\log_{10} R_1 + 10\log_{10}\left(\frac{4S_w}{R_2} + \frac{S_w}{2\pi r_2^2}\right) - TL + 0.1\ dB$	If r_2 > sqrt(Sw/2pi), then the wall emits something more like spherical waves
$L_{pA} = L_p + A(dB)$ $L_{pC} = L_p + C(dB)$	Weighted response: A weight ~ response at 40 dB SPL, C weight ~ response at 90 dB SPL

$$L_{eq} = 10\log_{10}\left[\frac{1}{N}\sum_{i=1}^{N} 10^{\frac{L_{pi}}{10}}\right]$$	Equivalent Level
$$L_{eq} = 10\log_{10}\left[\frac{1}{T}\sum_{i=1}^{N} t_i \times 10^{\frac{L_{pi}}{10}}\right]$$	Equivalent level
$$L_{DN} = 10\log_{10}\left[\frac{1}{24}\left(15 \times 10^{\frac{L_{AequivD}}{10}} + 90 \times 10^{\frac{L_{AequivN}}{10}}\right)\right]$$	Day-night level, using a 10 dB penalty for night (10pm to 7am)
$$E_{AT} = \int_0^T p_{Arms}^2(t)dt = 4T \times 10^{\frac{L_{Aeq}-100}{10}}$$	Sound exposure, proportional to acoustic energy
$$L_{AE} = 10\log_{10}\left[\frac{1}{p_{ref}^2}E_{AT}\right] = 10\log_{10}[T] + L_{Aeq}$$	Sound exposure level
Exceedance level Lx	Level exceeded X% of the time
$$SIL = K - 20\log_{10}(r^*)$$	SIL = average of SPL background noise within 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz octave bands K is SPL at 1m, depends on sex and voice level r* is distance less than which communication is possible
$$T_i = \frac{480}{2^{0.2(L_i-90)}}$$	Maximum allowable exposure duration at level L_i in minutes
$$D = \sum\left(\frac{t_i}{T_i}\right)$$	Noise dose – OSHA regs: D<0.5 OK; 0.5<D<1 monitor workers with yearly tests; D>1 illegal
What is a microphone?	Transducer that converts acoustic pressure into electrical signal
Condenser microphone	Functions like a parallel plate capacitor: sound-induced change in separation between diaphragm and backplate produces electrical current
Key characteristics of microphones	Sensitivity, freq. response, freq. range, dynamic range, directivity (polar) pattern
Different kind of microphone	Particle velocity measured by pairs of close pressure sensors (distance between sensors << wavelength)