

**Metric Prefixes**

peta	P	$10^{15}$	1 000 000 000 000 000
tera	T	$10^{12}$	1 000 000 000 000
giga	G	$10^9$	1 000 000 000
mega	M	$10^6$	1 000 000
kilo	k	$10^3$	1 000
hecto	h	$10^2$	100
deca	da	$10^1$	10
one		$10^0$	1
deci	d	$10^{-1}$	0.1
centi	c	$10^{-2}$	0.01
milli	m	$10^{-3}$	0.001
micro	$\mu$	$10^{-6}$	0.000 001
nano	n	$10^{-9}$	0.000 000 001
pico	p	$10^{-12}$	0.000 000 000 001
femto	f	$10^{-15}$	0.000 000 000 000 001

**Ohm's Law**  $V = IR$ ,  $I = \frac{V}{R}$ ,  $R = \frac{V}{I}$

**Battery Symbol**

The side with the longer line is the positive side

**Complex Numbers**

- $z = x + iy = re^{i\theta} = r[\cos(\theta) + i\sin(\theta)]$
- $[r(\cos(\theta) + i\sin(\theta))]^n = r^n[\cos(n\theta) + i\sin(n\theta)]$
- $z^n = (re^{i\theta}) = r^n e^{in\theta}$
- $\frac{1}{i} = -i$
- $\sqrt[n]{z} = \sqrt[n]{r} e^{\frac{\theta}{n} + \frac{2k\pi}{n}}$  for  $n \in N^*$  (ints  $\geq 0$ )
- $e^{j\theta} = \cos(\theta) + j\sin(\theta) \quad \left| \quad e^{-j\theta} = \cos(\theta) - j\sin(\theta) \right.$
- $\cos(\theta) = \frac{1}{2}(e^{j\theta} + e^{-j\theta}) \quad \left| \quad \sin(\theta) = \frac{1}{2j}(e^{j\theta} - e^{-j\theta}) \right.$
- normalized:  $\text{sinc}(t) = \frac{\sin(\pi t)}{\pi t}$

$$\left| \frac{a}{b} \right| = \frac{|a|}{|b|}$$

$$\angle \frac{a}{b} = \angle a - \angle b$$

**Trig**

$$\begin{aligned} \cos(2a) &= \cos^2(a) - \sin^2(a) = 2\cos^2(a) - 1 = 1 - 2\sin^2(a) \\ \cos^2(a) + \sin^2(a) &= 1 \quad \left| \quad \sin(2a) = 2\sin(a)\cos(a) \right. \\ \cos^2(a) &= \frac{1}{2}(1 + \cos(2a)) \quad \left| \quad \sin^2(a) = \frac{1}{2}(1 - \cos(2a)) \right. \end{aligned}$$

**Voltage Division between two non-zero points**

$$V_{DD} \rightarrow R_1 \rightarrow V_1 \rightarrow R_2 \rightarrow V_{EE} \quad (\text{superposition})$$

$$V_1 = V_{DD} \frac{R_2}{R_1 + R_2} + V_{EE} \frac{R_1}{R_1 + R_2}$$

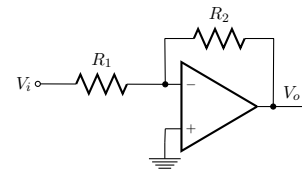
**Node Plots**

- magnitude is plotted in dB:  $|T(j\omega)|_{dB} = 20 \log_{10} |T(j\omega)|$
- starts on y-axis at DC offset with slope 0
- just add together the bode plots of each individual pole, zero, and the DC offset
- poles always slope down, zeros slope up (applies for both magnitude and phase)
- dec=decade, e.g. from  $10^0$  to  $10^1$
- magnitude:
  - \* Pole/Zero at origin: constant slope  $\pm 20\text{dB/dec}$  for all  $\omega$ ;  $0\text{dB}$  at  $\omega = 10^0 = 1$
  - \* Pole/Zero at  $\omega_0$ : 0 for  $\omega < \omega_0$  slope  $\pm 20 \frac{dB}{dec}$  after
  - \* Constant  $C$ : constant line at  $20 \log_{10}(|C|)$
- phase:
  - \* Pole at origin: constant  $-\frac{\pi}{2}$  or  $-90^\circ$
  - \* Zero at origin: constant  $+\frac{\pi}{2}$  or  $+90^\circ$
  - \* Pole/Zero at  $\omega_0$ : 0 for  $\omega < \frac{\omega_0}{10}$  slope linearly ( $\pm 45^\circ/\text{dec}$ ) until  $10\omega_0$  0 slope for  $\omega > 10\omega_0$
  - \* Constant  $C$ : no effect (0 for all  $\omega$ )

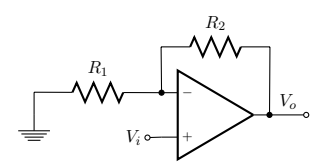
- Prof wants us to actually show the -3dB drop curve, not just a straight intersection

**Solving systems with Op Amps**

- only applies if the op-amp has feedback
- step 0: if the op amp is ideal, write out ideal properties:
  - \*  $V_+ = V_-$
  - \*  $I_- = 0, I_+ = 0$
  - \*  $A \approx \infty$
- avoid doing KCL/KVL directly on the output node of the op amp
- ignore resistors from a point at 0V to ground

**Op Amp Equations**

Inverting Amplifier



Non-Inverting Amplifier

- ideal open-loop behavior:  $(V_p - V_n) > 0 \rightarrow V_o = V_{DD}$   
 $(V_p - V_n) < 0 \rightarrow V_o = -V_{DD}$
- general form:  $T(s) = \frac{K_0}{1 + \frac{s}{\omega_0}}$ 
  - \*  $T(0) = K_0$ : DC offset. For these simple ones, it's equal to ideal response
  - \*  $\omega_0 = \frac{\omega_t}{1 + R_2/R_1}$
- inverting op amp:
  - \* ideal:  $T(s) = \frac{V_o}{V_i} = -\frac{R_2}{R_1}$
  - \* non-ideal:  $T(s) = \frac{V_o}{V_i} = \frac{-R_2/R_1}{1 + \frac{1 + R_2/R_1}{A(s)}} = \frac{-R_2/R_1}{1 + \frac{s}{\left(\frac{\omega_t}{1 + R_2/R_1}\right)}} = \frac{-R_2/R_1}{1 + \frac{s}{\omega_0}}$
- non-inverting op-amp:
  - \* ideal:  $T(s) = \frac{V_o}{V_i} = 1 + \frac{R_2}{R_1}$
  - \* non-ideal:  $T(s) = \frac{V_o}{V_i} = \frac{1 + R_2/R_1}{1 + \frac{1 + R_2/R_1}{A(s)}} = \frac{1 + R_2/R_1}{1 + \frac{s}{\left(\frac{\omega_t}{1 + R_2/R_1}\right)}} = \frac{1 + R_2/R_1}{1 + \frac{s}{\omega_0}}$

**MOS DC Biasing**

- this is all for NMOS. PMOS is backward
- cutoff:  $V_{GS} < V_{th}$ 
  - \*  $I_D = 0$
- triode (linear):  $V_{DS} < V_{GS} - V_{th}$ 
  - \*  $I_D = k'_n \frac{W}{L} \left( (V_{GS} - V_{th})V_{DS} - \frac{V_{DS}^2}{2} \right)$
- active (saturation):  $V_{DS} > V_{GS} - V_{th}$ 
  - \*  $I_D = \frac{k'_n}{2} \frac{W}{L} (V_{GS} - V_{th})^2$
  - \* overdrive voltage  $V_{ov} = V_{GS} - V_{th}$
- to show it's active: show that  $V_{DS} > V_{ov}$  or  $V_{DS} > V_{GS} - V_{th}$

**MOS Small Signal**

- $g_m = k'_n \frac{W}{L} (V_{GS} - V_t) = k'_p \frac{W}{L} (V_{SG} - V_t)$
- CS: Common Source
  - \*  $R_i = R_G = R_{G1} || R_{G2}$
  - \*  $R_o = R_D$
  - \*  $\frac{V_o}{V_g} = \frac{R_D || R_L}{\frac{1}{g_m} + R_S}$
- CD: Common Drain (buffer)
  - \*  $R_i = R_G = R_{G1} || R_{G2}$
  - \*  $R_o = \frac{1}{g_m}$
  - \*  $\frac{V_o}{V_g} = \frac{R_L}{\frac{1}{g_m} + R_L}$
- CG: Common Gate
  - \*  $R_i = \frac{1}{g_m}$
  - \*  $R_o = R_D$

$$*\frac{V_o}{V_s}=\frac{R_D||R_L}{R_i}$$