Basics and Op-Amps

$$\text{(Thevenin voltage)} \quad V_{TH} = V_{OC}$$

$$\text{(Norton current)} \quad I_N = I_{SC}$$

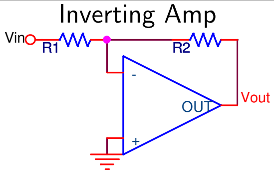
$$\text{(Equivalent impedance)} \quad R_{eq} = Z_{eq} = \frac{V_{OC}}{I_{SC}}$$

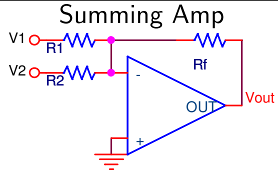
$$\text{(Equivalent admittance)} \quad Y_{eq} = \frac{I_{SC}}{V_{OC}}$$

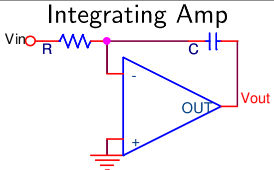
$$\text{(Parallel R+L/series C)} \quad x_{eq} = \frac{AB}{A+B}$$

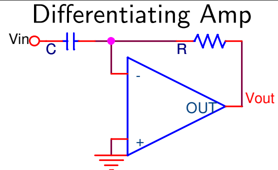
$$\text{(Root-mean-square of sine)} \quad V_{rms} = \sqrt{2}V_{max}$$

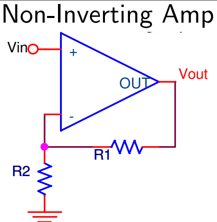
Op-Amps

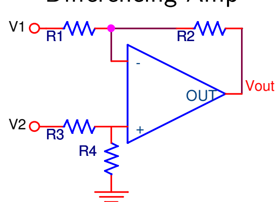
<table>
<tr><th colspan="2">Typical Op-Amp Filters</th></tr>
<tr>
<td>Inverting Amp


$V_{out} = -\frac{R_2}{R_1}V_{in}$</td>
<td>Summing Amp


$V_{out} = -\left(\frac{R_F}{R_1}V_1 + \frac{R_F}{R_2}V_2\right)$</td>
</tr>
<tr>
<td>Integrating Amp


$V_{out} = -\frac{1}{RC}\int V_{in}$</td>
<td>Differentiating Amp


$V_{out} = -RC\frac{dV_{in}}{dt}$</td>
</tr>
<tr>
<td>Non-Inverting Amp


$V_{out} = \frac{R_1+R_2}{R_2}V_{in}$</td>
<td>Differencing Amp


$V_{out} = -\frac{R_2}{R_1}V_1 + \frac{R_1+R_2}{R_1}\frac{R_4}{R_3+R_4}V_2$</td>
</tr>
</table>

Ideally, $Z_{in} = A_{OC} = CMR = GBWP = \infty$, $Z_{out} = SR = 0$

$$\text{(Diff. gain)} \quad A_d = \frac{R_2}{R_1} \text{ given } \frac{R_4}{R_3} = \frac{R_2}{R_1}$$

$$\text{(Diff. out)} \quad V_{out} = \Delta V A_d + |V|A_{cm}$$

$$\text{(Common mode rejection rate)} \quad CMRR = 20\log\frac{|A_d|}{|A_{cm}|}$$

$$\text{(Max frequency for slew rate on sin input)} \quad f_m = \frac{SR}{2\pi V_{max}}$$

$$\text{(Freq affects amp gain)} \quad GBWP = f_{3\,\mathrm{dB}}A$$

Offset voltage Voltage source V_{OS} connected in series between port and terminal of ideal op-amp.
Input Bias/Offset Current 2 current sources $I_{Bn} = I_B \pm .5 I_{OS}$ connected in parallel between port and terminal going to ground.

Semiconductors

$$q = 1.602 \times 10^{-19}\,\mathrm{C}$$

$$\varepsilon_s = 11.7\varepsilon_0 = 1.04 \times 10^{-12}\,\frac{\mathrm{F}}{\mathrm{cm}}$$

$$n = p = n_i = BT^{\frac{3}{2}}e^{\frac{-E_g}{2kT}}$$

$$B_{Si} = 7.3 \times 10^{15}\,\mathrm{cm}^{-3}\mathrm{K}^{\frac{-3}{2}}$$

$$E_{gSi} = 1.12\,\mathrm{eV}$$

$$k = 8.62 \times 10^{-5}\,\frac{\mathrm{eV}}{\mathrm{K}}$$

$$\text{For } N_D \gg n_i,\ n_n \approx N_D,\ p_n = \frac{{n_i}^2}{n_n} \approx \frac{{n_i}^2}{N_D}$$

$$\text{For } N_A \gg n_i,\ p_p \approx N_A,\ n_p = \frac{{n_i}^2}{p_p} \approx \frac{{n_i}^2}{N_A}$$

$$\text{(Built-in voltage)} \quad V_0 = \frac{kT}{q}\ln\left(\frac{N_A N_D}{{n_i}^2}\right)$$

$$\text{(Depletion region width)} \quad W = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 + V_R)}$$

$$x_p = W\frac{N_D}{N_A + N_D} \qquad x_n = W\frac{N_A}{N_A + N_D}$$

$$\text{(Junction charge)} \quad Q_J = Aq\left(\frac{N_A N_D}{N_A + N_D}\right)W$$

$$\mu_{pSi} = 480\,\frac{\mathrm{cm}^2}{\mathrm{Vs}} \qquad \mu_{nSi} = 1350\,\frac{\mathrm{cm}^2}{\mathrm{Vs}}$$

$$C_{ox} = \varepsilon_{ox}T_{ox}$$

Diodes

Ideal diodes are an open circuit when the voltage across them is negative (reverse bias), or a short circuit when the voltage across them is positive (forward bias).
Constant voltage drop is a very similarm model that goes to a short circuit at some forward voltage v_D, which is dropped across the diode once it turns on.
Zener diodes are used "backwards", so they can operate in the breakdown region. $V_Z = V_{Z0} + r_Z I_Z$

Rectifiers

$$\text{(Half-wave)} \quad PIV = V_s$$

$$\text{(Half-wave)} \quad V_o = v_S - v_D \text{ for } v_S \geq v_D$$

$$\text{(Full-wave)} \quad PIV = 2V_s - V_D$$

$$\text{(Full-wave)} \quad V_o = |v_S| - v_D \text{ for } |v_S| \geq v_D$$

$$\text{(Bridge)} \quad PIV = V_s - V_d$$

$$\text{(Bridge)} \quad V_o = |v_S| - 2v_D \text{ for } |v_s| \geq 2v_D$$

$$\text{(Half-wave Peak)} \quad i_{Dav} = I_L(1 + \pi\sqrt{2V_p/V_r})$$

$$\text{(Half-wave Peak)} \quad i_{Dmax} = I_L(1 + 2\pi\sqrt{2V_p/V_r})$$

$$\text{(Half-wave Peak)} \quad V_r = \frac{V_p}{fCR}$$

For full-wave peak, replace $\sqrt{2V_p/V_r}$ with $\sqrt{V_p/2V_r}$ and $V_r = \frac{V_p}{fCR}$ with $V_r = \frac{V_p}{2fCR}$.

Transistors

$$\textit{(Overdrive voltage)} \quad V_{OV} \equiv v_{GS} - V_t$$

n-channel

p-channel MOSFETs have the source (arrow) on bottom or the body arrow (if the body is not connected to the source) pointing in toward the circuit symbol.

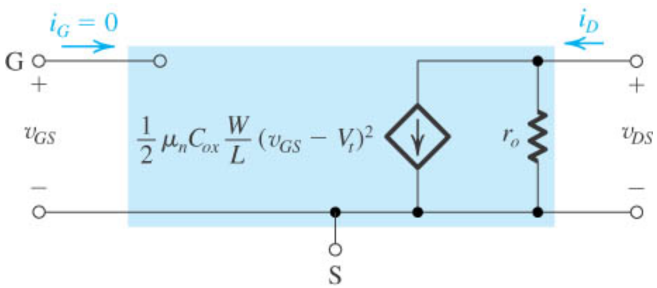
$$\textit{(Transconductance)} \quad k_n = \mu_n C_{ox} W/L = k'_n W/L$$

$$\textit{(Small-signal } R\textit{)} \quad r_{DS} = ((\mu_n C_{ox})(W/L)(v_{GS} - v_t))^{-1}$$

$$\textit{(Cutoff)} \quad i_D = 0 \qquad v_{GS} \le V_t$$

$$\textit{(Triode)} \quad i_D = k_n \left(V_{OV} - \tfrac{1}{2} v_{DS}\right) v_{DS} \qquad v_{DS} < V_{OV}$$

$$\textit{(Saturation)} \quad i_D = \tfrac{1}{2} k_n {V_{OV}}^2 (1 + \lambda v_{DS}) \qquad v_{DS} \ge V_{OV}$$



p-channel

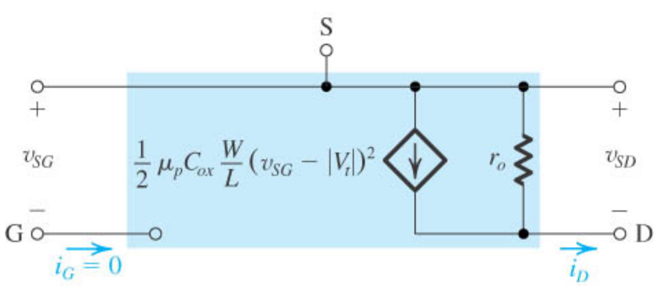
p-channel MOSFETs have the source (arrow) on top or the body arrow (if the body is not connected to the source) pointing out from the circuit symbol.

$$\textit{(Transconductance)} \quad k_p = \mu_p C_{ox} W/L = k'_p W/L$$

$$\textit{(Cutoff)} \quad i_D = 0 \qquad v_{SG} \le |V_t|$$

$$\textit{(Triode)} \quad i_D = k_n \left(|V_{OV}| - \tfrac{1}{2} v_{SD}\right) v_{SD} \qquad v_{SD} < |V_{OV}|$$

$$\textit{(Saturation)} \quad i_D = \tfrac{1}{2} k_n |V_{OV}|^2 (1 + |\lambda| v_{SD}) \qquad v_{SD} \ge |V_{OV}|$$



Small-Signal MOSFETs

$$g_m = \frac{dI_{DS}}{dV_{GS}} = k_n V_{OV} = \frac{2I_D}{V_{OV}}$$

$$\textit{(Early voltage)} \quad \lambda = 1/V_A \qquad r_o = \frac{V_A}{I_D}$$

MOSFET Amps

$$R_{in} = \infty \text{ for all but CG, where } R_{in} = \frac{1}{g_m}$$

$$R_o = R_D \text{ for all but SF, where } R_o = \frac{1}{g_m}$$

Amp	A_{vo}	A_v	G_v
CS	$-g_m R_D$	$-g_m(R_D \| \| R_L)$	$-g_m(R_D \| \| R_L)$
CS+R	$-\frac{g_m R_D}{1 + g_m R_s}$	$-\frac{g_m (R_D \| \| R_L)}{1 + g_m R_s}$	$-\frac{g_m (R_D \| \| R_L)}{1 + g_m R_s}$
CG	$g_m R_D$	$g_m(R_D \| \| R_L)$	$-\frac{R_D \| \| R_L}{R_{sig} + {g_m}^{-1}}$
SF	1	$\frac{R_L}{R_L + {g_m}^{-1}}$	$-\frac{R_L}{R_{sig} + {g_m}^{-1}}$

MOSFET current source

Connect MOSFETs gate to gate to get a current source/mirror:

$$\frac{I_{ref}}{W/L} = \frac{I_{D1}}{(W/L)_1} = \frac{I_{D2}}{(W/L)_2} = \cdots$$

Finding Frequency Response

- Assume saturation and find I_D, V_{GS}, V_{DS} for the bias point (Q-point), then ensure that the assumption is correct
- Use Q-point to estimate g_m, r_o
- Short DC voltages, coupling/bypass caps, open DC currents; analyze for A_v, R_{in}, R_{out}; estimate G_v

T model