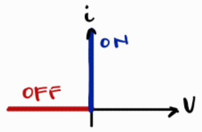
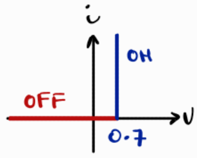
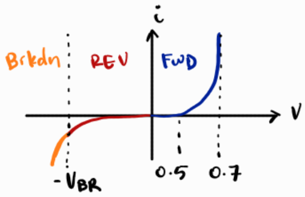
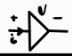






	OFF	ON
Assume	$i=0$	$V=0.7$
Verify	$V<0.4$	$i>0$

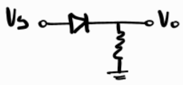
$i = I_s\left(e^{V/V_T} - 1\right)$ $V_T = \frac{kT}{q} \approx 25\,mV$

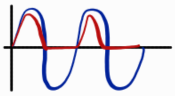
$i = I_s e^{V/V_T}$ $V = V_T \ln(i/I_s)$ $V_2 - V_1 = V_T \ln(i_2/i_1)$

for the same current, $-2mV/1°C$ temp increase

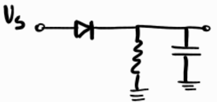
Diodes

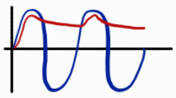
half-wave rectifier



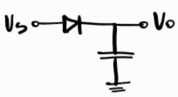


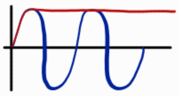
peak rectifier





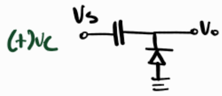
peak detector

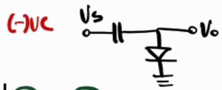


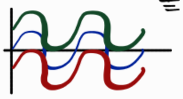


$V_{ripple} = \frac{V_{peak}}{fRC}$ if $\tau = RC \gg T = \frac{1}{f}$

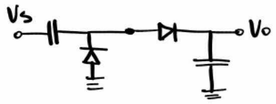
clamped capacitor

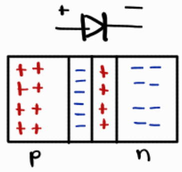




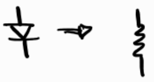


voltage double: clamper + peak detector



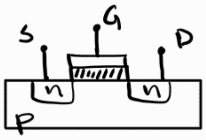


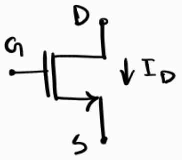
diode in small signal



$r_d = \frac{V_T}{I_D}$

MOSFETs

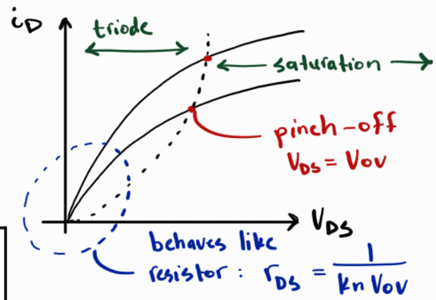




$V_{ov} = V_{GS} - V_t$

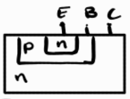
$\underbrace{\underbrace{\mu_n C_{ox}}_{k_n'} (W/L)}_{k_n}$

	Source	Drain	I_D
Cutoff (open swtch)	$V_{GS} \le V_t$		0
Triode (V.cntr. R)	$V_{GS} > V_t$	$V_{GD} > V_t$, $V_{DS} < V_{ov}$	$k_n\left[V_{ov}V_{DS} - \frac{V_{DS}^2}{2}\right]$
Saturation (V.cntr. I_s)	$V_{GS} > V_t$	$V_{GD} \le V_t$, $V_{DS} \geq V_{ov}$	$\frac{1}{2}k_n V_{ov}^2[1 + \lambda V_{DS}]$



behaves like resistor: $r_{DS} = \frac{1}{k_n V_{ov}}$

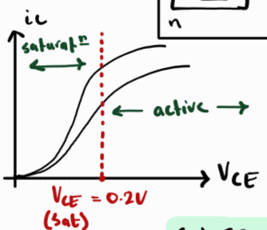
BJTs



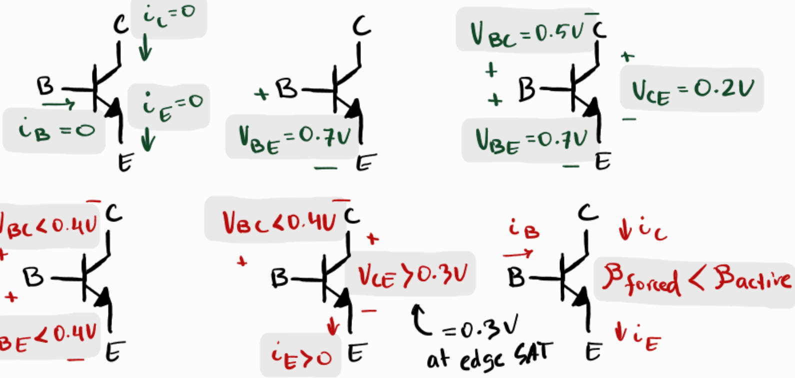
$i_C = I_s e^{V_{BE}/V_T}\left[1 + \frac{V_{CE}}{V_A}\right]$ $\alpha = \frac{\beta}{\beta+1}$ $\beta = \frac{\alpha}{1-\alpha}$

$i_B = \frac{i_C}{\beta} = \frac{i_E}{\beta+1}$ $i_E = i_C + i_B = (\beta+1)i_B$

$i_C = \beta i_B = \alpha i_E$



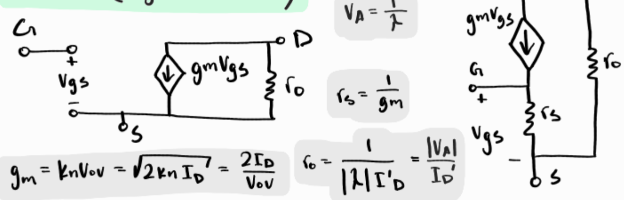
	Cutoff	Active (Ctrl. I_s)	Saturation
Assume	$i_C=0$, $i_E=0$, $i_B=0$	$V_{BE}=0.7V$	$V_{BC}=0.5V$, $V_{BE}=0.7V$, $V_{CE}=0.2V$
Verify	$V_{BC}<0.4V$, $V_{BE}<0.4V$	$V_{BC}<0.4V$, $V_{CE}>0.3V$, $i_E>0$; $=0.3V$ at edge SAT	$\beta_{forced} < \beta_{active}$



Transistor Small Signal Models

MOSFET in saturation, BJT in active

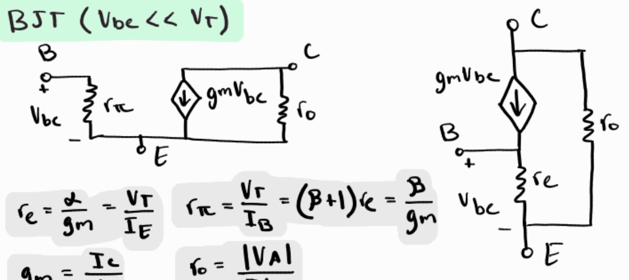
MOSFET ($V_{gs} \ll 2V_{ov}$)



$V_A = \frac{1}{\lambda}$ $r_s = \frac{1}{g_m}$

$g_m = k_n V_{ov} = \sqrt{2k_n I_D} = \frac{2I_D}{V_{ov}}$ $r_o = \frac{1}{|\lambda| I_D'} = \frac{|V_A|}{I_D'}$

BJT ($V_{be} \ll V_T$)



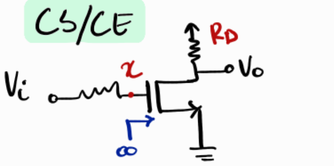
$r_e = \frac{\alpha}{g_m} = \frac{V_T}{I_E}$ $r_\pi = \frac{V_T}{I_B} = (\beta+1)r_e = \frac{\beta}{g_m}$

$g_m = \frac{I_C}{V_T}$ $r_o = \frac{|V_A|}{I_C'}$

Transistor Amplifiers:

[gate/base can never be output] [drain/collector can never be input] [CD: source flwr] [CC: emitter flwr]

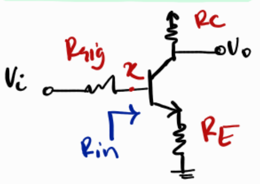
CS/CE



$\frac{V_o}{V_x} = -\frac{\text{drain resistance}}{\text{source resistance}} = -\frac{R_D}{1/g_m} = -g_m R_D$

$\frac{V_o}{V_i} = \frac{V_o}{V_x} = -g_m R_D$

CS/CE w/ resistor

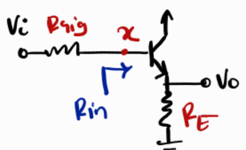


$\frac{V_o}{V_x} = -\frac{\text{collector resistance}}{\text{emitter resistance}} = -\frac{\alpha R_C}{\frac{\alpha}{g_m} + R_E} = -\frac{\alpha R_C}{r_e + R_E}$

$R_{in} = r_\pi + (\beta+1)r_e$ or $= (\beta+1)(r_e + R_E)$

$\frac{V_o}{V_i} = \frac{V_x}{V_i} \cdot \frac{V_o}{V_x} = \frac{R_{in}}{R_{sig} + R_{in}} \cdot \left(-\frac{\alpha R_C}{r_e + R_E}\right)$

CD/CC (follower)

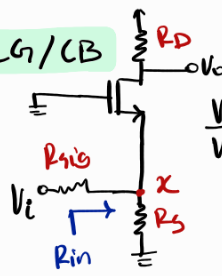


$\frac{V_o}{V_x} = \frac{R_E}{\frac{\alpha}{g_m} + R_E}$ or $\frac{R_E}{r_e + R_E}$

$R_{in} = r_\pi + (\beta+1)R_E$ or $(\beta+1)(r_e + R_E)$

$\frac{V_o}{V_i} = \frac{V_x}{V_i} \cdot \frac{V_o}{V_x} = \frac{R_{in}}{R_{sig} + R_{in}} \cdot \frac{R_E}{r_e + R_E}$

CG/CB

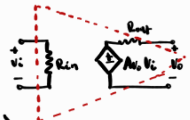


$R_{in} = R_s \,//\, 1/g_m$

$\frac{V_o}{V_x} = \frac{\text{drain resistance}}{\text{source resistance}} = \frac{R_D}{1/g_m} = g_m R_D$

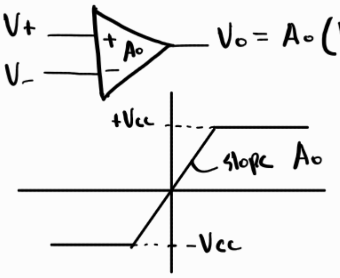
$\frac{V_o}{V_i} = \frac{V_x}{V_i} \cdot \frac{V_o}{V_x} = \frac{R_{in}}{R_{sig} + R_{in}} \cdot g_m R_D$

Op Amps



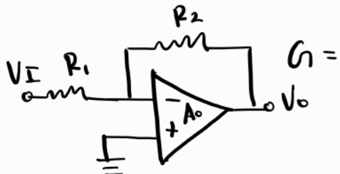
Ideal:

1) $i_+ = i_- = 0$ (opamp)
2) $V_- = V_+$ (negative feedback)



$$V_o = A_o(V_+ - V_-)$$

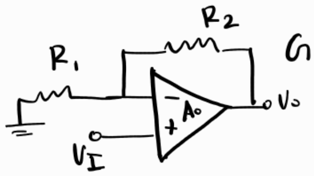
Inverting Config:



$$G = \frac{V_o}{V_I} = \frac{-\frac{R_2}{R_1}}{1 + \frac{(1 + R_2/R_1)}{A_o}}$$

← K

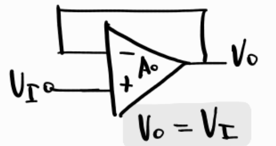
Non inverting Config:



$$G = \frac{V_o}{V_I} = \frac{1 + \left(\frac{R_2}{R_1}\right)}{1 + \frac{(1 + R_2/R_1)}{A_o}}$$

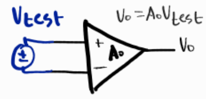
← K

Unity Gain Buffer



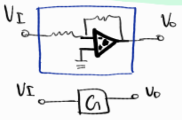
$$V_o = V_I$$

Open loop gain



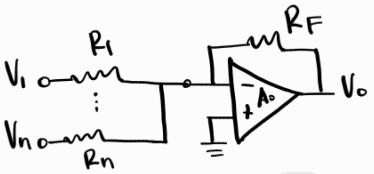
A_o: op amp gain (no feedback)(device)

Closed loop gain



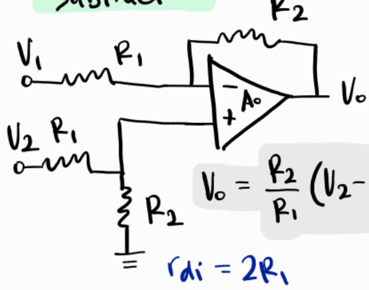
$G: \frac{V_o}{V_I} \left(= -\frac{R_2}{R_1}\right)$ ex

Weighted Sum Amplifier



$$V_o = -R_F\left(\frac{V_1}{R_1} + \dots + \frac{V_n}{R_n}\right)$$

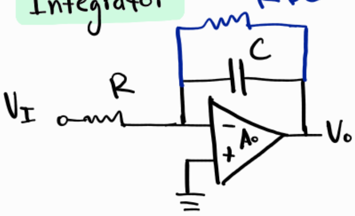
Subtractor



$$V_o = \frac{R_2}{R_1}(V_2 - V_1)$$

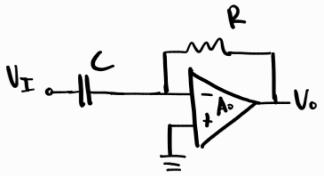
$r_{di} = 2R_1$

Integrator



$$V_o = -\frac{1}{RC}\int V_I \, dt$$

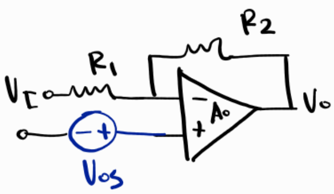
Differentiator



$$V_o = -RC\frac{d}{dt}V_I$$

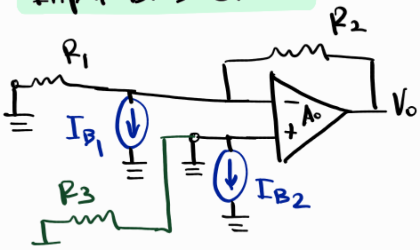
DC Imperfections

Offset Voltage



can compensate by adding capacitor for AC signals

Input Bias Current



compensate by adding

$R_3 = R_1 \| R_2$

Large Signal Limitations:

1) V_{omax} : max output voltage
2) I_{omax} : max output current
3) Slew rate : max rate of change of the output voltage

Full pwr Bandwidth (f_M):

$$f_M = \frac{SR}{2\pi V_{omax}}$$

halfwave : $PIV = V_S$

fullwave : $PIV = 2V_S - V_D$

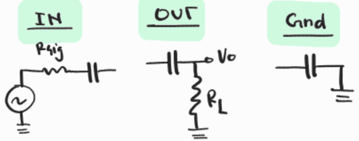
bridge : $PIV = V_S - V_D$

$\sin(\theta) = \cos(\theta - \frac{\pi}{2})$

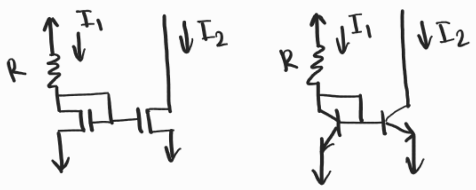
$\cos(\theta) = \sin(\theta + \frac{\pi}{2})$

$\omega = 2\pi f$

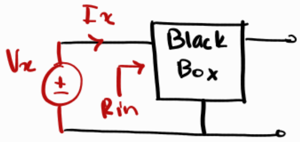
$$x(t) = x(\infty) + [x(t_0^+) - x(\infty)]e^{-(t-t_0)/\tau}$$



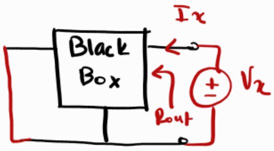
Current Mirrors



$$\frac{I_1}{I_2} = \frac{(W/L)_1}{(W/L)_2} \qquad \frac{I_1}{I_2} = \frac{A_1}{A_2}$$



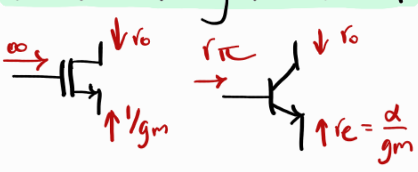
$$R_{in} = \frac{V_x}{I_x}$$



$$R_{out} = \frac{V_x}{I_x}$$

If there is a resistor attatched to the source, use T-model. Else use pi-model.

Resistance looking into terminal



$$P_{avg} = \frac{1}{2}V_{pk} \cdot I_{pk} = V_{rms} \cdot I_{rms} \quad \text{where } V_{rms} = \frac{1}{\sqrt{2}}V_{pk},\ I_{rms} = \frac{1}{\sqrt{2}}I_{pk}$$

	R_{in}	A_{vo}	R_o
CS:	∞	$-g_m R_D$	R_D
CS.r:	∞	$\frac{-g_m R_D}{1+g_m R_S}$	R_D
CG:	$\frac{1}{g_m}$	$g_m R_D$	R_D
CD.f:	∞	1	$\frac{1}{g_m}$
CE:	$(\beta+1)r_e$	$-g_m R_C$	R_C
CE.r:	$(\beta+1)(r_e+R_e)$	$\frac{-g_m R_C}{1+g_m R_e}$	R_C
CB:	r_e	$g_m R_C$	R_C
CC.f:	$(\beta+1)(r_e+R_L)$	1	r_e

	A_v	G_v
CS:	$-g_m(R_D \| R_L)$	$= A_v$
CS.r:	$\frac{-g_m(R_D \| R_L)}{1+g_m R_S}$	$= A_v$
CG:	$g_m(R_D \| R_L)$	$\frac{R_D \| R_L}{R_{sig} + 1/g_m}$
CD.f:	$\frac{R_L}{R_L + 1/g_m}$	$= A_v$
CE:	$-g_m(R_C \| R_L)$	$\frac{-\beta(R_C \| R_L)}{R_{sig} + (\beta+1)r_e}$
CE.r:	$\frac{-g_m(R_C \| R_L)}{1+g_m R_e}$	$\frac{-\beta(R_C \| R_L)}{R_{sig} + R_{in}}$
CB:	$g_m(R_C \| R_L)$ or $\alpha\frac{R_C \| R_L}{r_e}$	$\alpha\frac{R_C \| R_L}{R_{sig} + r_e}$
CC.f:	$\frac{R_L}{R_L + r_e}$	$\frac{R_L}{R_L + r_e + \frac{R_{sig}}{\beta+1}}$