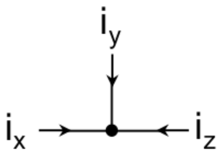
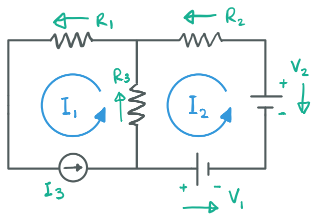
ULTIMATE GUIDE TO BASIC CONCEPTS

1. KCL



$i_x + i_y + i_z = 0$

2. KVL



Same direction +, opp direction -

$I_1 = I_3$

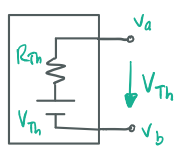
$I_1(R_1+R_3) - I_2(R_3) = 0$

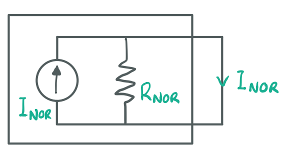
$V_1 - V_2 + I_2(R_2+R_3) - I_1(R_3) = 0$

3. Superposition

- Choose 1 Source
- Short circuit V Source
- Open circuit I Source
- Calculate V_1 / I_1
- Repeat for all sources & Sum up

4. Thevenin & Norton





Finding $R_{Th} = R_{NOR}$:

- Short Circuit V source
- Open Circuit I source

$V_{Th} = I_{NOR} R_{Th}$

5. AC Signals

$v(t) = v_{rms}\sqrt{2}\sin(\omega t + \theta)$

$v_{ave} = \frac{1}{T}\int_0^T v(t)\,dt$

$v_{rms} = \frac{V_p}{\sqrt{2}} = \sqrt{\frac{1}{T}\int_0^T v^2(t)\,dt}$

$\omega = 2\pi f$

positive phase shift
=
wave moves left

6. Phasors

$$\underbrace{re^{j\theta} = r\angle\theta}_{\text{Polar}} = \underbrace{\overbrace{r\cos(\theta)}^{\text{Real}} + \overbrace{rj\sin(\theta)}^{\text{Imaginary}}}_{\text{Rectangular}}$$

rms value

7. Capacitors

$i(t) = C\frac{dv(t)}{dt}$

$X_c = \frac{1}{j\omega C}$

Open Circuit in DC Analysis $(f = 0Hz)$

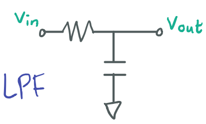
8. Inductor

$v(t) = L\frac{di(t)}{dt}$

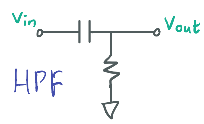
$X_L = j\omega L$

Short Circuit in DC Analysis

9. Passive LPF & HPF



LPF



HPF

$H(j\omega) = \frac{1}{j\omega CR+1}$ Gain $H(j\omega) = \frac{j\omega CR}{j\omega CR+1}$

$f_{3dB} = \frac{1}{2\pi RC}$

Power in dB $= 10 \cdot \log\left(\frac{P_{out}}{P_{in}}\right)$

Voltage in dB $= 20 \cdot \log\left(\frac{V_{out}}{V_{in}}\right)$

Power in dBm $= 10 \cdot \log\left(\frac{P_{out}}{1mW}\right)$

10. Average Power

$P_{ave} = \frac{1}{T}\int_0^T p(t)\,dt$

$= i_{rms} \cdot v_{rms} \cdot \cos\left|\theta_i - \theta_v\right|$

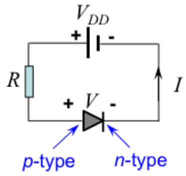
Apparent Power $= v_{rms} \cdot i_{rms}$ [VA] aka V-I rating

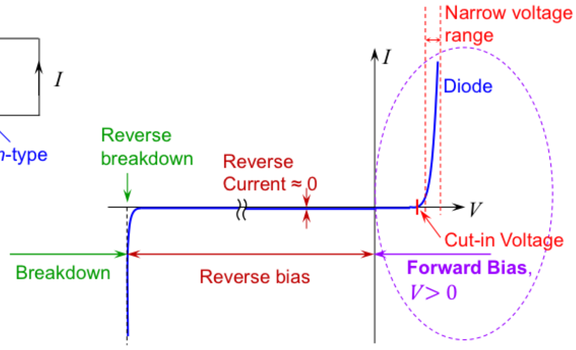
Power Factor $= \frac{P_{ave}}{\text{App Power}}$ if $\theta_i = \theta_v$, PF = 1

Diodes

Anode
p-type

Cathode
n-type





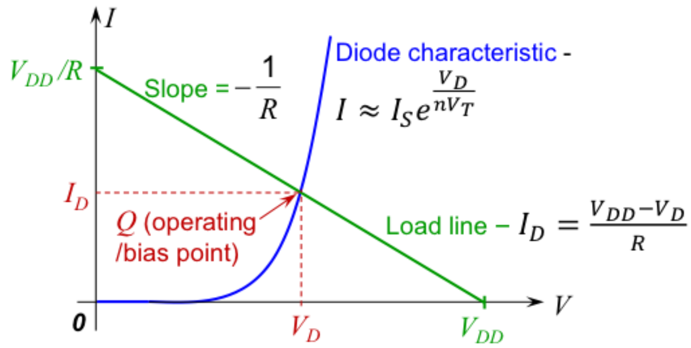
FORWARD BIAS

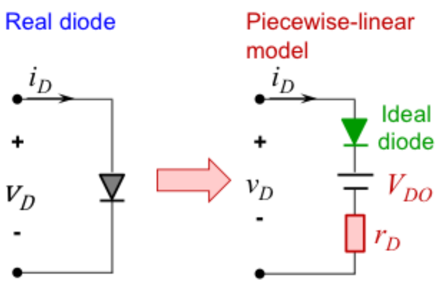
$V > 0$

Higher voltage @p-type terminal Wrt n-type terminal
current flows through the diode from the p-type to n-type side

$I = I_S e^{\frac{V}{nV_T}}$ $\quad V = nV_T \ln\left(\frac{I}{I_S}\right)$

Q point : Intersection of Ohm's law & Diode characteristic





Use this if provided

AC Analysis

When adding small AC Source:

$i_D(t) = I_D + i_d(t)$

$i_d(t) = v_d(t) / r_d$

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

REVERSE BIAS

$V < 0$, $|V| < V_Z$

Lower voltage @p-type terminal wrt n-type terminal
Current flows through the diode from the n-type to p-type side

$I = -I_S$

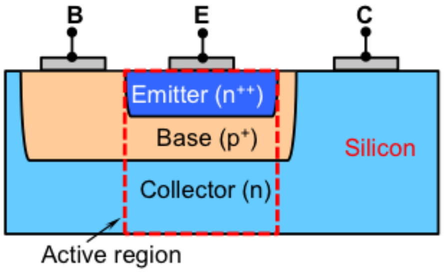
BREAKDOWN REGION

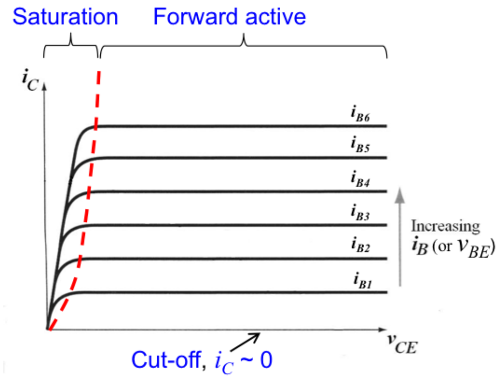
$V < 0$, $V_{DD} > V_Z$

Voltage across diode stays constant @ $-V_Z$
Polarity & current direction same as Reverse Bias

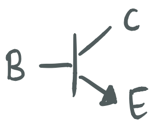
$I = \frac{V_{DD} - V_Z}{R}$

BJT





NPN



	V_{BE}	V_{BC}	
Cut-off	−	−	OFF
Forward Active	+	−	Amp
Saturation	+	+	ON
Reverse Active	−	+	X

FORWARD ACTIVE

$i_c = I_s e^{V_{BE}/V_T}$ (without Early Effect)

$i_c = I_s e^{V_{BE}/V_T} \left(1 + \frac{V_{CE}}{V_A}\right)$ (with Early Effect)

$i_c = \beta i_B$

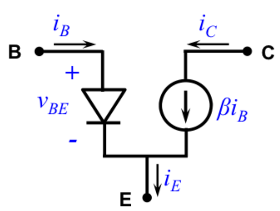
$i_E = i_c + i_B$

$V_{BE} = 0.7V$

$i_E = (\beta+1) i_B$

$= \left(\frac{1}{\beta}+1\right) i_c$

LARGE SIGNAL MODEL



PNP

	V_{EB}	V_{CB}	
Cut-off	−	−	OFF
Forward Active	+	−	Amp
Saturation	+	+	ON
Reverse Active	−	+	X

FORWARD ACTIVE

$i_c = I_s e^{V_{EB}/V_T}$ (without Early Effect)

$i_c = I_s e^{V_{EB}/V_T} \left(1 + \frac{V_{EC}}{V_A}\right)$ (with Early Effect)

$i_c = \beta i_B$

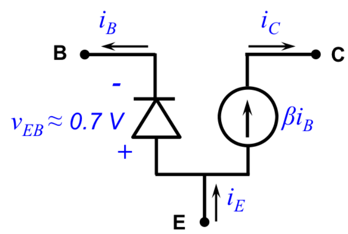
$i_E = i_c + i_B$

$V_{EB} = 0.7V$

$i_E = (\beta+1) i_B$

$= \left(\frac{1}{\beta}+1\right) i_c$

LARGE SIGNAL MODEL

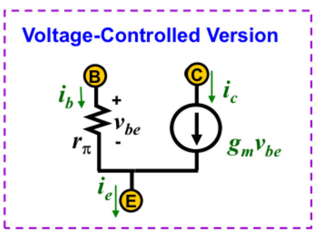


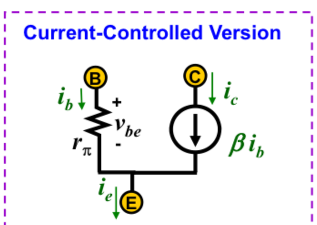
SMALL SIGNAL MODEL (Same for Both)

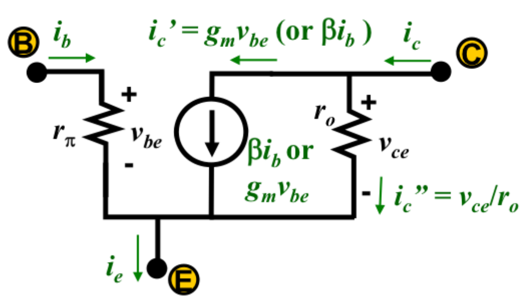
$g_m = \frac{i_c}{v_{be}} = \frac{I_c}{V_T}$

$r_\pi = \frac{\beta}{g_m}$

$r_o = \frac{V_{ce}}{i_c} = \frac{V_A}{I_c}$ (Hybrid)



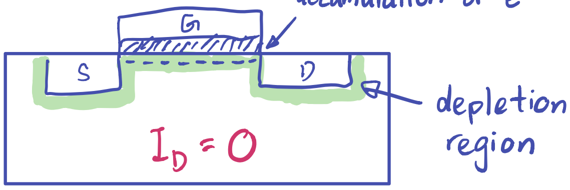




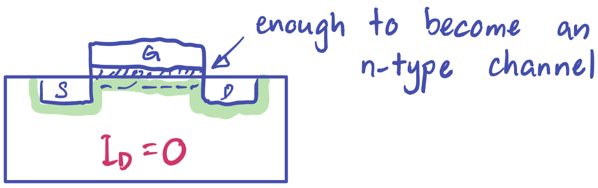
MOSFET

THE MOSFET STORY (using n-channel)

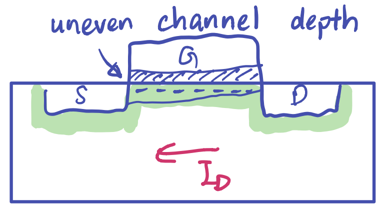
1. $0 < V_{GS} < V_{Th}$: Cut-off Region



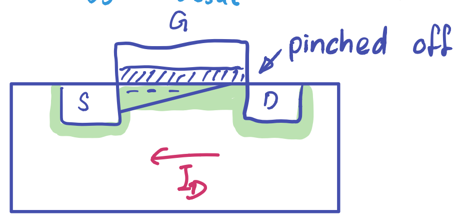
2. $V_{GS} \geq V_{Th}$

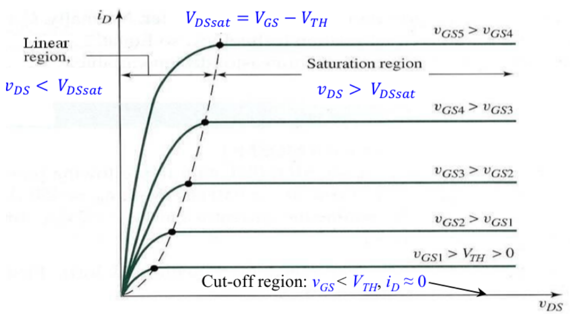


3. $V_{DS} > 0$: Linear Region



4. $V_{DS} > V_{DSsat}$: Saturation Region





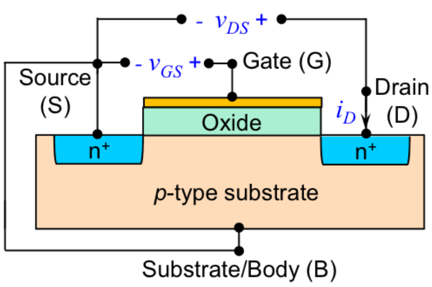
$I_G = 0A$

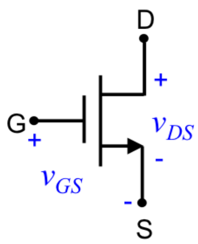
$V_{DSsat} = V_{GS} - V_{Th}$

If D & G are shorted, MOSFET is always in Saturation (true for both types)

$K_n = \frac{1}{2} \mu \frac{W}{L} C_{ox}$

N-CHANNEL

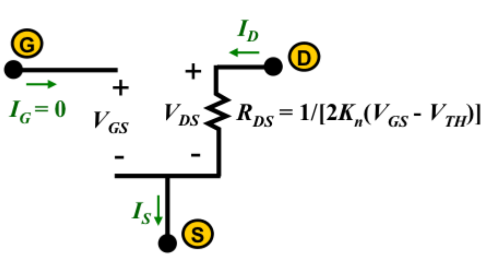




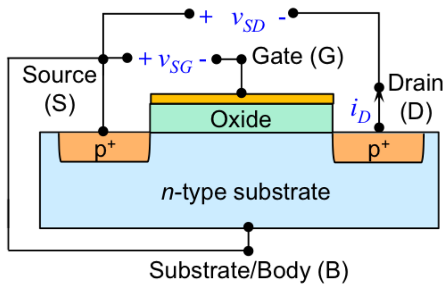
Cut-off	$V_{GS} < V_{Th}$		OFF
Linear	$V_{GS} > V_{Th}$	$V_{DS} < V_{GS} - V_{Th}$	ON
Saturation	$V_{GS} > V_{Th}$	$V_{DS} > V_{GS} - V_{Th}$	Amp

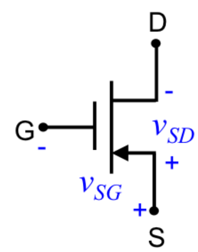
LINEAR REGION

$i_D = 2K_n\left[(V_{GS} - V_{Th})V_{DS} - 0.5V_{DS}^2\right]$



P-CHANNEL

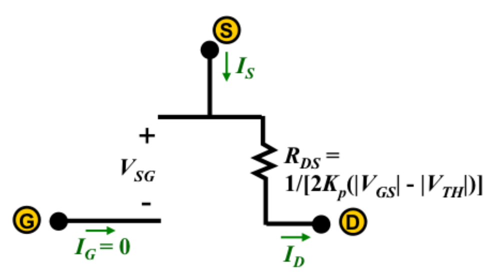




Cut-off	$V_{SG} < \lvert V_{Th} \rvert$		OFF
Linear	$V_{SG} > \lvert V_{Th} \rvert$	$V_{SD} < V_{SG} - \lvert V_{Th} \rvert$	ON
Saturation	$V_{SG} > \lvert V_{Th} \rvert$	$V_{SD} > V_{SG} - \lvert V_{Th} \rvert$	Amp

LINEAR REGION

Put modulus on all Voltages

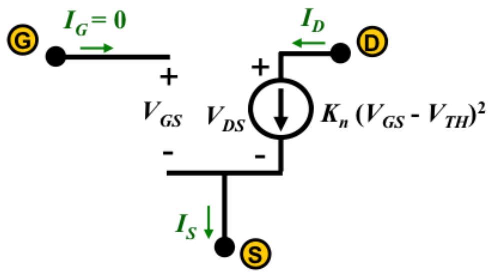


SATURATION REGION

$i_D = K_n (v_{GS} - V_{Th})^2$ (w/o CLME)

$i_D = K_n (v_{GS} - V_{Th})^2 (1 + \lambda v_{DS})$ (w/ CLME)

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

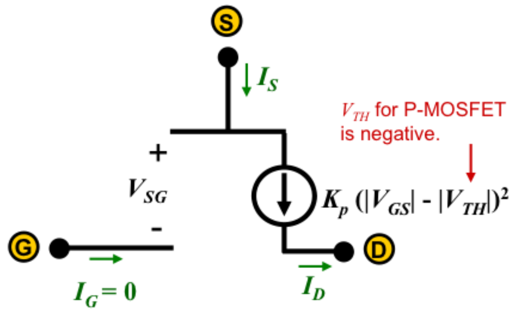


SMALL SIGNAL MODEL

$g_m = \frac{i_d}{v_{gs}} = 2K_n (V_{GS} - V_{Th}) = 2\sqrt{K_n I_D}$

SATURATION REGION

Put modulus on all Voltages

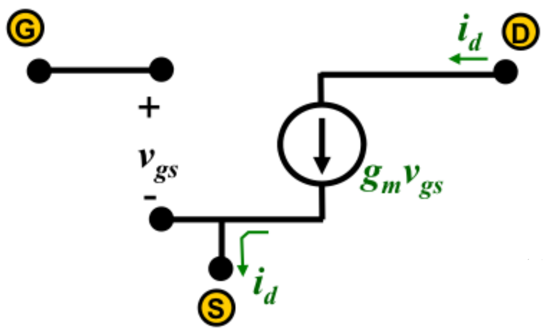


SMALL SIGNAL MODEL

$g_m = \frac{i_d}{v_{sg}} = 2K_p (V_{SG} - |V_{Th}|) = 2\sqrt{K_p I_D}$

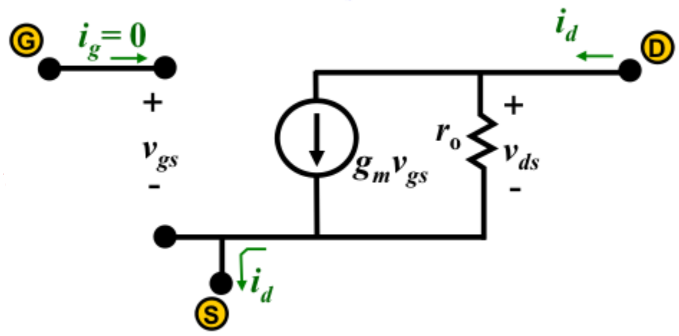
$r_o = \frac{v_{ds}}{i_d} = \frac{V_A}{I_D}$

Hybrid-π Model for N-MOSFET or P-MOSFET



Hybrid-π Model with Output Resistance

(The dependence of i_D on v_{DS} is accounted for)

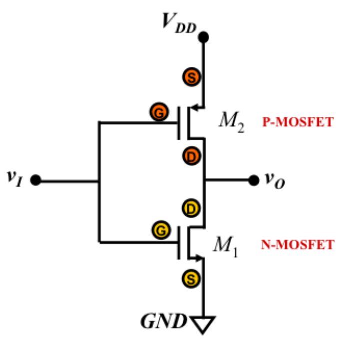


BODY EFFECT

When Body is not tied to source

$g_{mb} = \frac{i_d}{v_{sb}}$

CMOS INVERTER



Pull up Network

Pull down Network

v_I is HIGH

↓

PMOS is cutoff

NMOS is linear or Sat

↓

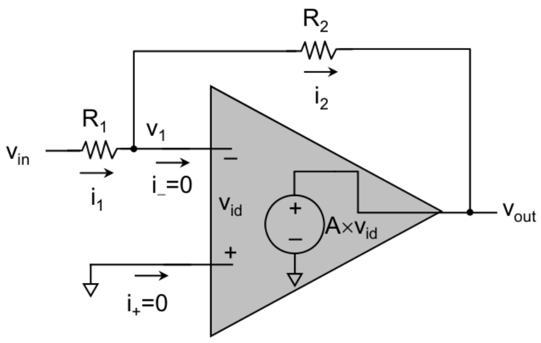
v_O is LOW

$$\frac{t_{pHL}}{t_{pLH}} = \frac{\dfrac{1}{\mu_n \left(\dfrac{W}{L}\right)_N}}{\dfrac{1}{\mu_p \left(\dfrac{W}{L}\right)_P}}$$

Dynamic Power Dissipation = $fC_L V_{DD}^2$

THE ULTIMATE GUIDE TO OP-AMPS

THE OP AMP



$R_{in} = \infty$
$R_{out} = 0$
$A = \infty$

In Circuit Analysis:
$i_- = 0$
$i_+ = 0$

$i_1 = i_2$

$v_+ = v_1$ (virtual short)

Open Loop (SSA) vs **Feedback (Op-Amp) Amplifiers**

Open Loop (SSA)
- difficult to control gain
- Simple
- ↓ Power consumption
- Poor Linearity / ↑ Distortion

Feedback (Op-Amp) Amplifiers
- Accurate gain rfm Resistors
- Complicated
- ↑ Power Consumption
- High Linearity / ↓ Distortion

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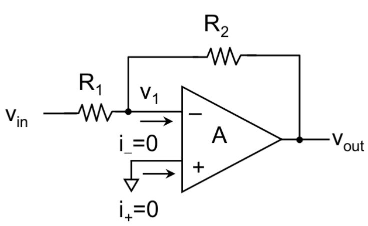
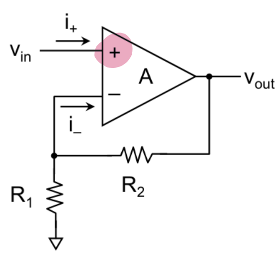
1. INVERTING AMP



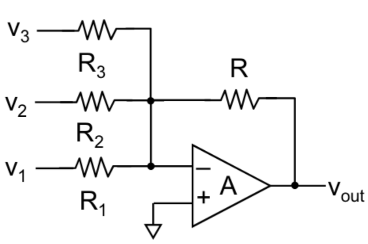
$$V_{out} = -\frac{R_2}{R_1} V_{in}$$

3. NON-INVERTING AMP



$$V_{out} = \left(1 + \frac{R_1}{R_2}\right) V_{in}$$

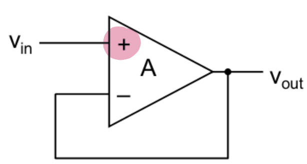
2. SUMMING AMP



Using Superposition

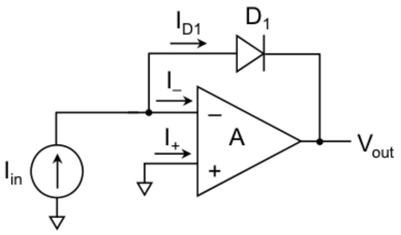
$$V_{out} = -R\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right)$$

4. SOURCE FOLLOWER



$$V_{out} = V_{in}$$

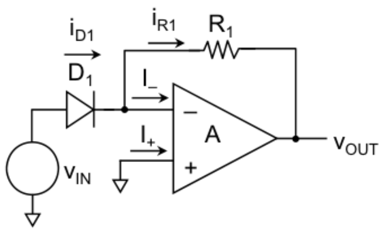
5. LOGARITHMIC AMP



$$V_{out} = -V_T \ln\left(\frac{I_{in}}{I_s}\right)$$

Good for inputs with a wide range

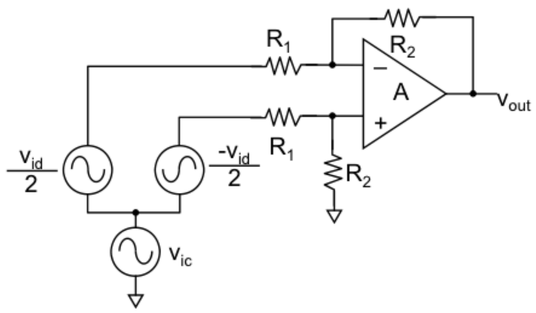
6. EXPONENTIAL AMP



$$V_{out} = -R_1 I_s e^{V_{in}/V_T}$$

Good for inputs with a small range

7. INSTRUMENTATION AMP



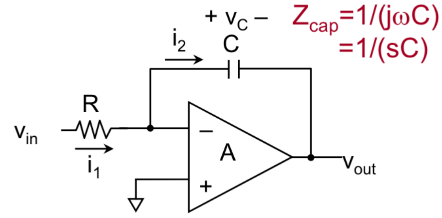
$$V_{out} = -\frac{R_2}{R_1}(V_{id})$$

Rejects Common mode, Amplifies differential

Good for blocking noise

Used in measuring instruments

8. INTEGRATOR



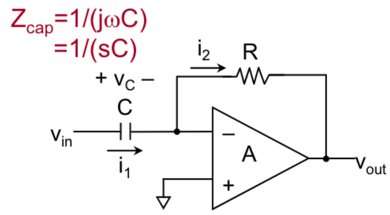
$$V_{out}(t) = -\frac{1}{RC}\int_0^t V_{in}(t)\,dt$$

$$H(j\omega) = -\frac{Z_{cap}}{R}$$

* Use on ⊓⊔⊓⊔⊓ to get ⩘⩘⩘ !

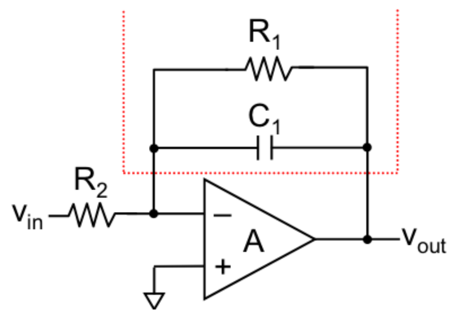
Gain ↓ as freq ↑

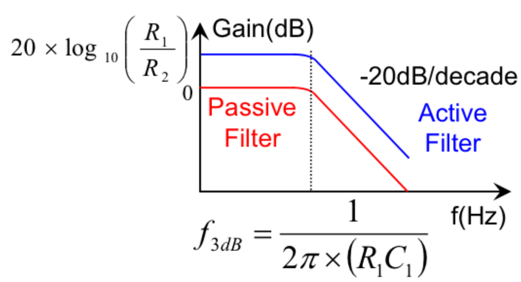
9. DIFFERENTIATOR



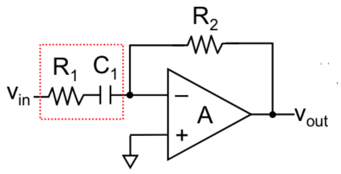
$$V_{out}(t) = -RC\frac{d}{dt}V_{in}(t)$$

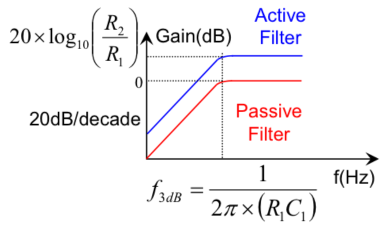
10. 1st ORDER LOWPASS



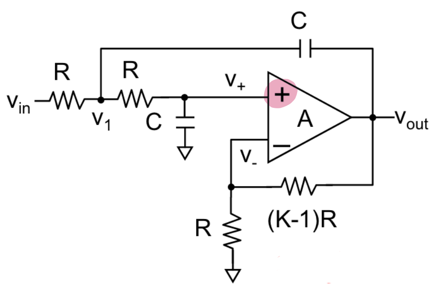


11. 1st ORDER HIGHPASS



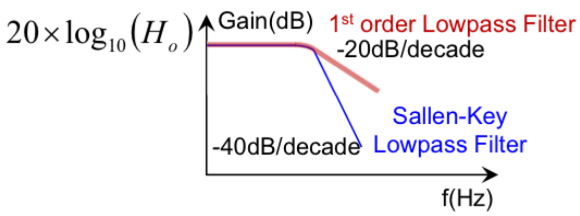


12. 2nd ORDER SALLEN-KEY LOWPASS FILTER

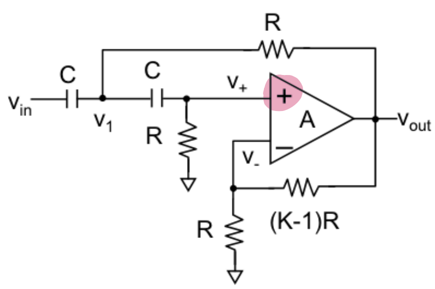


$\omega_0 = \frac{1}{RC}$ $\frac{1}{Q} = 3-K$ $H_0 = K$

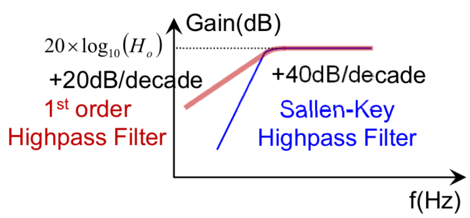
@Low freq $H(j\omega) \approx H_0$
@High freq $H(j\omega) \approx H_0\omega_0^2/(j\omega)^2$



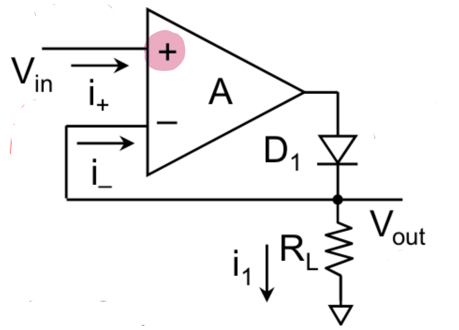
13. 2nd ORDER SALLEN-KEY HIGHPASS FILTER

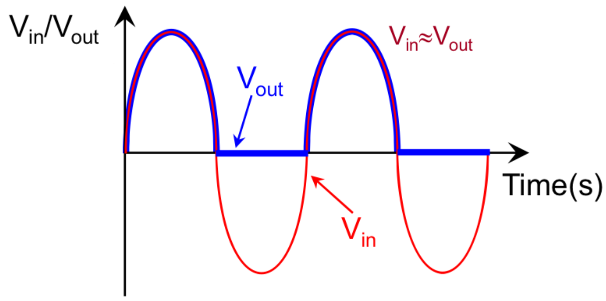


@Low freq, $H(j\omega) \approx H_0\,(j\omega)^2/\omega_0^2$
@High freq, $H(j\omega) \approx H_0$

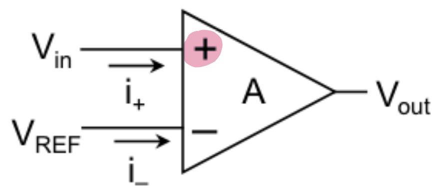


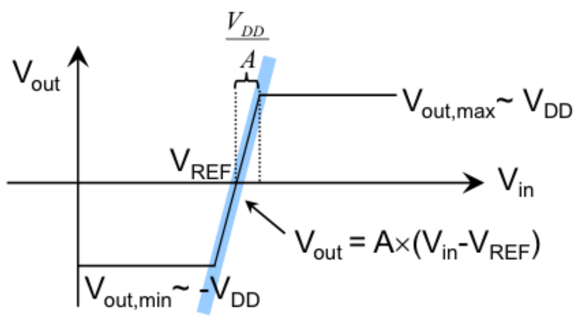
14. SUPERDIODE RECTIFIER





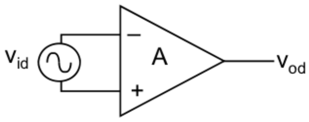
15. COMPARATOR



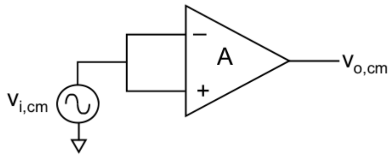


OP AMP PARAMETERS

Open Loop Voltage Gain (A_{OL}): How well the desired signal is amplified



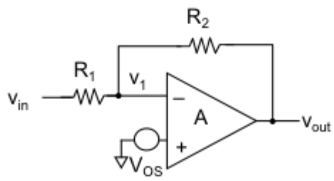
Common Mode Voltage Gain (A_{CM}): How much noise is amplified
Ideal value is 0



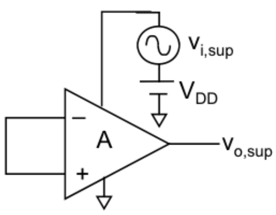
Common Mode Rejection Ratio (CMRR): How well noise is rejected
Ideal is ∞

$$CMRR\,[dB] = 20\log\left(\frac{A_{OL}}{A_{CM}}\right)$$

Input Offset Voltage (V_{OS}): DC output shift
Use superposition to find new V_{out}



Power Supply Rejection Ratio (PSRR): How well supply line ripples are rejected.
Ideal is ∞



GBW

$$f_{3dB,CL} = 2\pi\ GBW \times \frac{R_1}{R_1+R_2}$$

$$f_{3dB,OL} = GBW \div A_{OL}$$

$$A_{sup} = \frac{V_{o,sup}}{V_{i,sup}}$$

$$PSRR\,[dB] = 20\log\left(\frac{A_{OL}}{A_{sup}}\right)$$

Slew Rate (SR): Maximum slope that can occur @ output

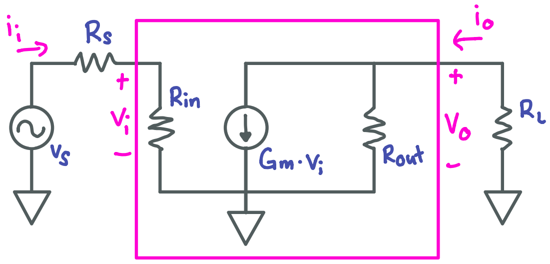
$$SR = 2\pi f \cdot V_{out,pk} \cdot \sin(2\pi f t)$$

... & Many More!

THE ULTIMATE Guide TO SINGLE-STAGE amplifiers

by Rachelle! v1

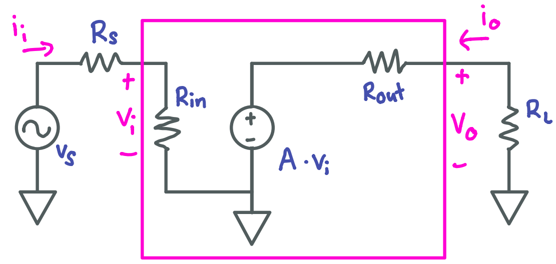
Transconductance Amplifier



- High R_{in}
- High R_{out}
- Voltage-to-current: $G_m v_i$

$$\text{Gain} = \frac{R_{in}}{R_s + R_{in}} \times G_m \times (R_{out} \,//\, R_L)$$

Voltage Amplifier



- High R_{in}
- Low R_{out}
- Voltage gain A

DC ANALYSIS

1. Remove Source & Load
2. ⊣⊢ Open circuit
3. BJT / MOSFET Analysis

BJT

$$g_m = \frac{I_C}{V_T}$$

$$r_\pi = \frac{\beta}{g_m}$$

$$r_o = \frac{V_A}{I_C}$$

MOSFET

$$g_m = 2K_n(V_{GS} - V_{TH}) = 2\sqrt{K_n I_D}$$
$$= 2I_D/(V_{GS} - V_{TH})$$

$$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right) I_D}$$

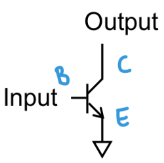
For Body Effect, $g_{mb} \approx -\frac{g_m}{4}$

$r_i = \infty$

$r_o = \frac{1}{\lambda_n I_D}$

8 AMPLIFIERS

Common Emitter (CE)



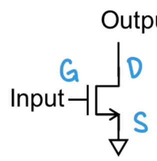
Use Transconductance Amp

$G_m = g_m$

R_{in} : Table 1A

R_{out} : Table 1B

Common Source (CS)



Use Transconductance Amp

$G_m = g_m$

R_{in} : ∞

R_{out} : r_o

CE/CS Characteristics

High R_i

High R_o

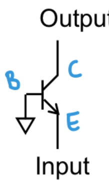
Medium Gain

V_{in} & V_{out} has opp sign

↑ G_m & R_o means higher A_v

BJT g_m > MOS g_m

Common Base (CB)



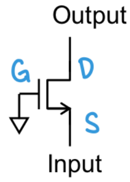
Use Transconductance Amp

$G_m = -g_m$

R_{in} : Table 1C

R_{out} : Table 1B

Common Gate (CG)



Use Transconductance Amp

$G_m = g_{mb} - g_m$

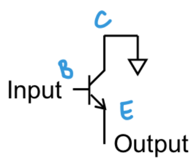
R_{in} : Table 2D

R_{out} : Table 2B

CB/CG Characteristics

Low R_i	V_{in} & V_{out} has same sign
High R_o	$\uparrow G_m$ & R_o means higher A_v
Medium Gain	BJT g_m > MOS $g_m - g_{mb}$

Common Collector (CC)



Use Voltage Amplifier

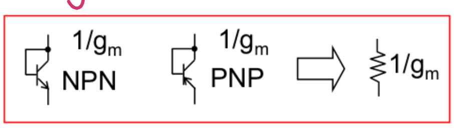
$$A_v = \frac{g_m R_L}{1 + g_m R_L}$$

$$\approx 1 \quad \text{if } g_m R_L >> 1$$

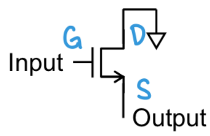
R_{in} : Table 1A

R_{out} : Table 1C

☆ May be able to do:



Common Drain (CD)



Use Voltage Amplifier

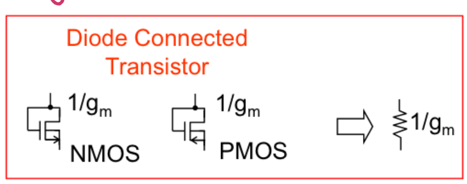
$$A_v = \frac{g_m R_L}{1 + (g_m - g_{mb}) R_L}$$

$$\approx \frac{g_m}{g_m - g_{mb}} \quad \text{if } (g_m - g_{mb}) R_L >> 1$$

R_{in} : ∞

R_{out} : Table 2C

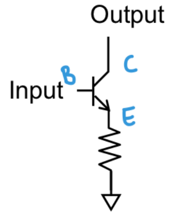
☆ May be able to do:



CC/CD Characteristics

High R_i	V_{in} & V_{out} has same sign
Low R_o	Ideal buffer
≈ Ideal Gain	BJT g_m > MOS $g_m - g_{mb}$

CE w/ Degeneration

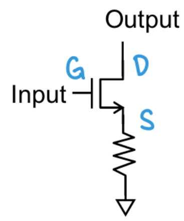


Use Transconductance Amp

$G_m \approx \frac{g_m}{1+g_m R_E}$

R_{in} : Table 1A
R_{out} : Table 1B

CS w/ Degeneration



Use Transconductance Amp

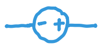
$G_m = \frac{g_m}{1+(g_m - g_{mb})R_E}$

R_{in} : ∞
R_{out} : Table 2B

Degenerates
High R_i
High R_o
Lower gain than w/o Degeneration

V_{in} & V_{out} has opp sign

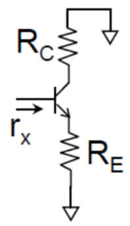
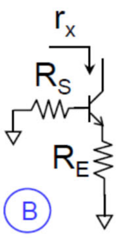
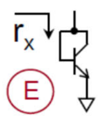
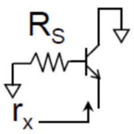
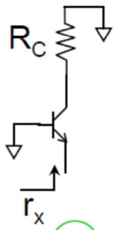
AC Analysis

1.  ⇒ Ground
2.  ⇒ Open Circuit
3.  ⇒ Short Circuit
4. BJT / MOSFET ⇒ small signal AC Model (Personally I don't see how this helps)
5. Find R_{in}, R_{out}, G_m / A_v

VI. Single-Stage Amplifier Analysis

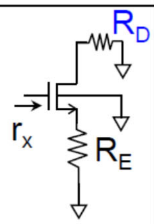
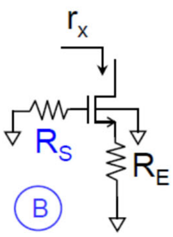
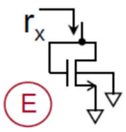
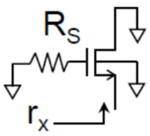
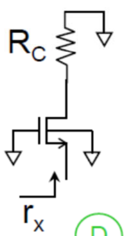
BJT Equivalent Resistance Summary (Table 1)

Blue: look into collector terminal   Red: look into base terminal   Green: look into emitter terminal

Conf	r_x	Conf	r_x	Conf	r_x
 A	$r_\pi + (1+\beta)R_E$ $\approx r_\pi(1+g_m R_E)$ $If \;\; R_E = 0$ $r_x = r_\pi$	 B	$r_o\left\{1+g_m\left[(r_\pi+R_S)//R_E\right]\left(\frac{r_\pi}{r_\pi+R_S}\right)\right\}$ $If \;\; R_S = 0 \;\; and \;\; r_\pi << R_E$ $\Rightarrow r_{x,\max} = r_o(\beta+1)$ $If \;\; R_E = 0, \;\; r_x = r_o$	 E	$\frac{1}{g_m}$
 C	$\frac{R_S + r_\pi}{1+\beta} // r_o$ $\approx \frac{R_S}{1+\beta} + \frac{1}{g_m}$ $If \; R_S = 0$ $r_x \approx \frac{1}{g_m}$	 D	$\frac{1}{g_m} \times \frac{r_o + R_C}{r_o + R_C/\beta}$ $If \; R_C = 0, r_x \approx \frac{1}{g_m}$		

MOS Equivalent Resistance Summary (Table 2)

Blue: look into drain terminal   Red: look into gate terminal   Green: look into source terminal

Conf	r_x	Conf	r_x	Conf	r_x
 A	∞	 B	$r_o\left[1+(g_m-g_{mb})R_E\right]$ $If \;\; R_E = 0, r_x = r_0$	 E	$\frac{1}{g_m}$
 C	$\frac{1}{g_m - g_{mb}}$	 D	$\frac{1}{g_m - g_{mb}} \times \frac{r_o + R_C}{r_o}$ $If \; R_C = 0, r_x \approx \frac{1}{g_m - g_{mb}}$		