ECE 2151 ANALOG ELECTRONIC CIRCUITS (E&C)

Symbols and Notations:

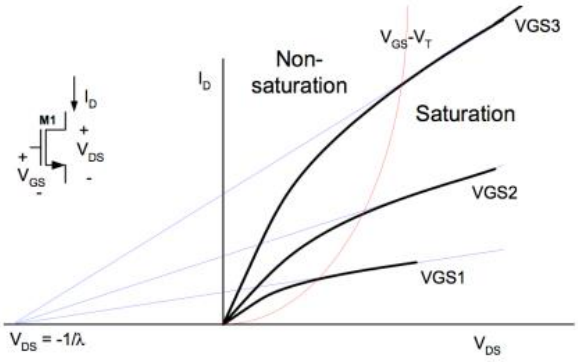
Symbol	Name	Unit
V_T	threshold Voltage	V
V_{GS}	gate to Source Voltage	V
I_{DS}	drain Current	mA
V_{DS}	drain to Source Voltage	V
$\mu_n C_{ox} \frac{W}{L}$		A/V^2
μ_n	mobility of charge carriers	$cm^2/(V\text{-}s)$
C_{ox}	gate capacitance per unit area	F/cm^2
$\frac{W}{L}$	aspect ratio	-
λ	channel-length modulation coefficient	V^{-1}
gm	trans conductance	S
r_0	mos output impedance	Ω
$C_{Mi} = (1 - A_v)C_f$	miller Capacitance (input)	F
A_v	voltage Gain (Mosfet)	-
C_{Mo}	miller Capacitance (output)	F
A_F	voltage gain with feedback (opamp)	-
S	slew rate	V/μS
A_{DM}	Differential mode gain	
A_{CM}	Common mode gain	
K	Feedback factor	
R_{in}	Input resistance without feedback	Ω
R_{out}	Output resistance without feedback	Ω
A_V	Voltage gain without feedback	
A_I	Current gain without feedback	
R_O	Transresistance without feedback	Ω
G_m	Transconductance without feedback	S
H(S)	Transfer function	

MOSFET EQUATIONS:

N channel MOSFET:

Cut off	$V_{GS} \leq V_T$	$I_{DS} = 0$
Linear	$V_{GS} > V_T, V_{DS} \leq V_{GS} - V_T$	$I_{DS} = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right](1 + \lambda V_{DS})$
Saturation	$V_{GS} > V_T, V_{DS} > V_{GS} - V_T$	$I_{DS} = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_T)^2(1 + \lambda V_{DS})$

MOSFET Characteristics:



MOS Transconductance:

$$\mathrm{gm} = \frac{\partial I_D}{\partial V_{\mathrm{GS}}}$$

$$g_m = \mu_n C_{\mathrm{ox}} \frac{W}{L}(V_{\mathrm{GS}} - V_T)$$

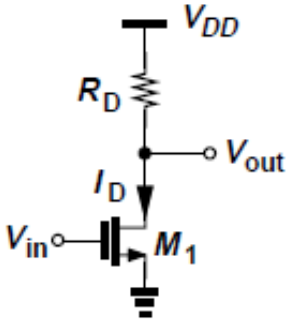
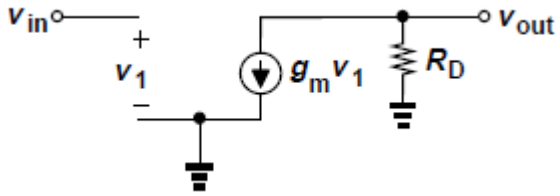
$$g_m = \sqrt{2\mu_n C_{\mathrm{ox}} \frac{W}{L} I_D}$$

$$g_m = \frac{2I_D}{V_{\mathrm{GS}} - V_T}$$

MOS Drain to Source Resistance:

$$r_0 \approx \frac{1}{\lambda I_D}$$

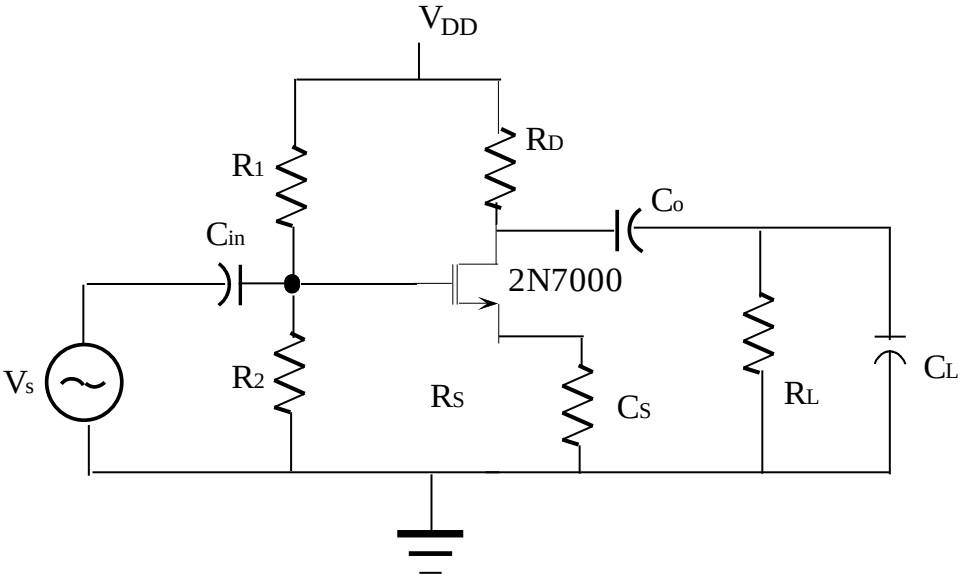
MOS Amplifiers:

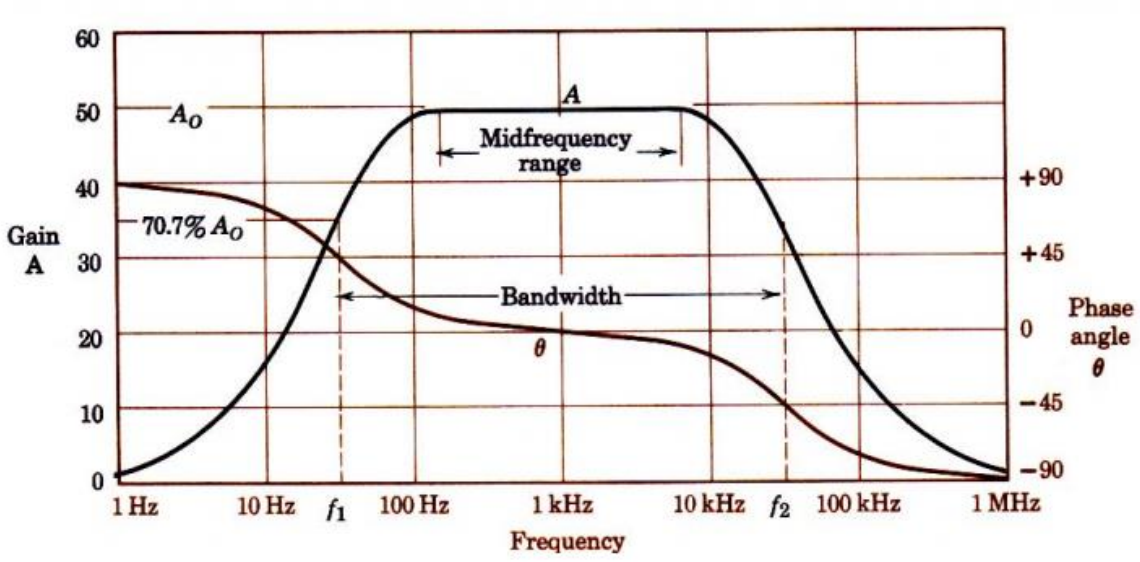
Common-source stage	Small-signal model
	

Differential Amplifiers:

Common mode to differential mode conversion (A_{CM-DM}) (effect of asymmetries, for load resistor mismatch)	$\left\lvert\frac{\Delta V_{out}}{\Delta V_{CM}}\right\rvert = \frac{\Delta R_D}{\frac{1}{g_m} + 2R_{SS}}$

RC Coupled Amplifier frequency Response:





Determination Of Coupling And Bypass Capacitors:

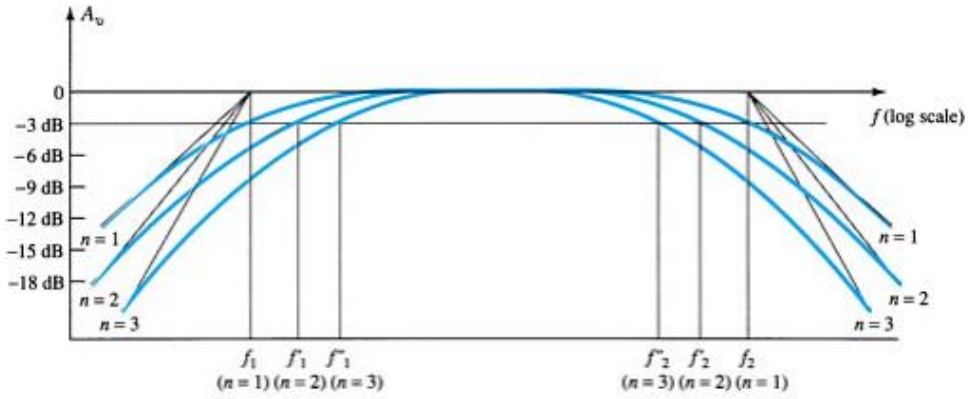
$X_{\text{Cin}} \vee \frac{1}{2\pi f_L C_{\text{in}}}$ and $X_{\text{Cin}} \vee R_i = R_1 \vee R_2$

$$|X_{\text{Co}}| = \frac{1}{2\pi f_L \text{Co}} \text{and} |X_{\text{Co}}| = (R_D \| \text{ro}) + R_L$$

$$|X_{\text{CL}}| = \frac{1}{2\pi f_H C_L} \text{and} \vee X_{\text{CL}} \vee (R_D \vee R_L \vee r_o)$$

$$|\text{Xcs}| = \frac{1}{2\pi f_L \text{Cs}} \text{and} |\text{Xcs}| = \left(\text{Rs} \| \frac{1}{g_m}\right)$$

Multistage Amplifier Frequency Response:



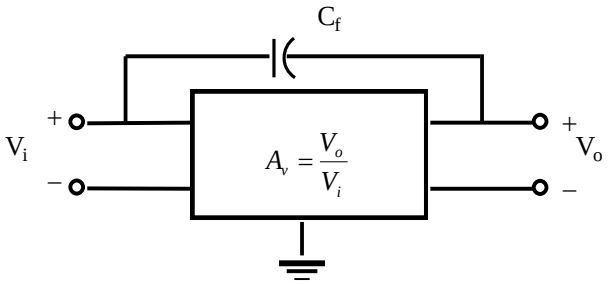
The lower cut off frequency of multistage MOSFET Amplifier is

$f_1' = \frac{f_1}{\sqrt{2^{\frac{1}{n}}-1}}$ where f_1 is lower cut off frequency of a single stage MOSFET Amplifier

The higher cut off frequency of multistage MODFET Amplifier is

$f_2' = f_2\sqrt{2^{\frac{1}{n}}-1}$ where f2 is upper cut off frequency of a single stage MOSFET Amplifier

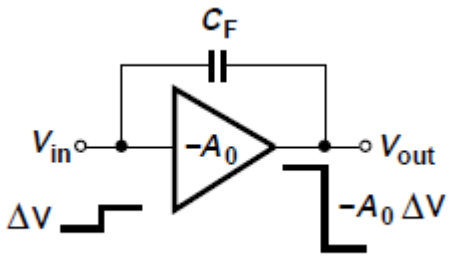
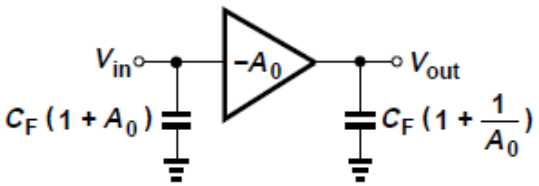
Miller Capacitance:



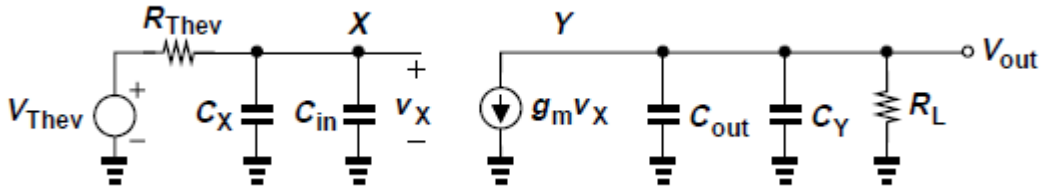
$$C_{\text{Mi}} = (1 - A_v)C_f$$

$$C_{\text{Mo}} = \left(1 - \frac{1}{A_v}\right)C_f$$

Miller's theorem:

Inverting circuit with floating capacitor	Circuit as obtained from Miller's theorem.
	

High-Frequency Response

Unified model

Pole frequencies are: $\lvert\omega_{pin}\rvert$ $\lvert\omega_{pout}\rvert$ C_{XY}tied between X and Y.

OPAMP CIRCUITS:

Inverting Configuration: $A_F = \frac{-R_F}{R_1}$

Non-Inverting Configuration: Gain$A_F = 1 + \frac{R_F}{R_1}$

Slew Rate

S$\frac{\Delta V_O}{\Delta T}$ v/μsec

At any frequency fs, and at a definite gain the maximum value of undistorted output voltage $V_{max} = \frac{S}{2\Pi fs}$v where S is the slew rate of the Opamp.

Diode Current $I = I\left(e^{\frac{V}{\eta V_T}} - 1\right)$	I: diode current Io: diode reverse saturation current at room temperature V: external voltage applied to the diode ŋ: = a constant, 1 for Ge, and 2 for Si V_T: Thermal voltage V_T = kT/q = T/11600, volt-equivalent of temperature K: Boltzmann's constant (1.38066×10^{-23} J/K) q: charge of an electron (1.60219×10^{-19} C) T: temperature of the diode junction in ^oK ($273^o + {}^oC$)
BJT Fixed Bias $S = 1 + \beta$	S: Stability factor β: Common-emitter current gain
BJT self-bias $S = (1 + \beta)\frac{1 + \frac{R_B}{R_E}}{1 + \beta + \frac{R_B}{R_E}}$	S: Stability factor β: Common-emitter current gain R_B: Base Resistor R_E: Emitter Resistor
BJT	$I_{B\max}$: Maximum Base current

$I_{B\max} = \frac{I_{\text{CSat}}}{\beta_{\text{dc}}}$	I_{CSat}: Collector saturation current β_{dc}: Common-emitter current gain
$P_D = (T_J\text{-}T_A)/\ \Theta_{J\text{-}A}$	P_D: Power dissipated in the transistor T_J: Junction temperature in ^oC T_A: Ambient temperature in ^oC $\Theta_{J\text{-}A}$: Thermal resistance from junction to ambience
$P_D = (T_J\text{-}T_C)/\ \Theta_{J\text{-}C}$	P_D: Power dissipated in the transistor T_J: Junction temperature in ^oC T_C: Case temperature in ^oC $\Theta_{J\text{-}C}$: Thermal resistance from junction to case
$\Theta_{J\text{-}A} = \Theta_{J\text{-}C} + \Theta_{C\text{-}A}$	$\Theta_{J\text{-}A}$: Thermal resistance from junction to ambience $\Theta_{J\text{-}C}$: Thermal resistance from junction to case $\Theta_{C\text{-}A}$: Thermal resistance from case to ambience
Small Signal Model of BJT:	
$r_{\text{ac}} = \beta r_e$	r_{ac}: Resistance looking in to the base of transistor β: *Common-emitter current gain* $r_e = \frac{26\text{mV}}{I_E}$; I_E= Emitter current
C.E amplifier in fixed bias circuit	
$Z_i = R_B \vee \beta\ r_e$	Z_i: Input impedance R_B: Base resistor β: *Common-emitter current gain* $r_e = \frac{26\text{mV}}{I_E}$; I_E= Emitter current
$Z_O = r_O \parallel R_C$	Z_O: Output impedance r_O: Output resistance R_C: Collector resistor
$A_V = \frac{-R_c \vee r_O}{r_e}$	A_V: Voltage gain R_C: Collector resistor r_O: Output resistance $r_e = \frac{26\text{mV}}{I_E}$; I_E= Emitter current
CE amplifier in Voltage divider Biasing	
$Z_i = R^1 \vee \beta r_e$	Z_i: Input impedance $R^1 = R_1 \vee R_2$ β: Common-emitter current gain $r_e = \frac{26\text{mV}}{I_E}$; I_E= Emitter current
$Z_o = R_C \vee r_O$	Z_o: Output impedance R_C: Collector resistor r_O: Output resistance
$A_v = \frac{-(R_C \vee r_O)}{r_e}$	A_v: Voltage gain R_C: Collector resistor r_O: Output resistance $r_e = \frac{26\text{mV}}{I_E}$; I_E= Emitter current
CC configuration	
$Z_i = R_B \vee Z_b$	Z_i: Input impedance R_B: Base resistor
$Z_b = \beta r_e + (1+\beta)R_E$	Z_b: Impedance looking in to the base terminal β: Common-emitter current gain $r_e = \frac{26\text{mV}}{I_E}$;

	I_E= Emitter current, R_E: Emitter resistor
$Z_O = r_e \vee R_E$	Z_O: Output impedance r_e= $\frac{26\text{mV}}{I_E}$; I_E= Emitter current R_E: Emitter resistor
$A_v = \frac{R_E}{R_E + r_e}$	A_v: Voltage gain r_e= $\frac{26\text{mV}}{I_E}$; I_E= Emitter current R_E: Emitter resistor
Field Effect Transistor (JFET)	
$\mu = g_m r_d$	μ: Amplification factor g_m: Trans-conductance r_d: Dynamic drain resistance
$I_{\text{DS}} = I_{\text{DSS}}\left(1 - \frac{V_{\text{GS}}}{V_P}\right)^2$	I_{DS}: Drain to source current I_{DSS}: Drain saturation current at pinch-off V_{GS}: Gate to source voltage V_P: Pinch-off voltage (= $\lvert V_{\text{GS(off)}}\rvert$)
$V_{\text{GS}} = V_P\left(1 - \sqrt{\frac{I_D}{I_{\text{DSS}}}}\right)$	V_{GS}: Gate to source voltage V_P: Pinch-off voltage (= $\lvert V_{\text{GS(off)}}\rvert$) I_D: Drain current I_{DSS}: Drain saturation current at pinch-off
$V_{DSmin} = V_{GS} - V_P$	V_{DSmin}: Minimum drain to source voltage V_{GS}: Gate to source voltage V_P: Pinch-off voltage (= $\lvert V_{\text{GS(off)}}\rvert$)
Enhancement Type MOSFET	
$V_{\text{DS(Sat)}} = V_{\text{GS}} - V_T$	$V_{\text{DS(Sat)}}$: Drain to source saturation V_{GS}: Gate to source voltage V_T: Threshold voltage
$I_D = k$	I_D: Drain Current k: Constant V_{GS}: Gate to source voltage V_T: Threshold voltage
$k = \frac{I_{D(\text{ON})}}{\left(V_{GS(ON)} - V_T\right)^2}$	k: Constant $I_{D(\text{ON})}$: Drain current corresponding to $V_{\text{GS(ON)}}$ $V_{\text{GS(ON)}}$: Gate to source voltage at which channel is ON. V_T: Threshold voltage
Depletion MOSFET	
$I_D = I_{\text{DSS}}\left(1 - \frac{V_{\text{GS}}}{V_P}\right)^2$	I_{DS}: Drain to source current I_{DSS}: Drain saturation current at pinch-off V_{GS}: Gate to source voltage V_P: Pinch-off voltage
FET Amplifiers:	
$g_{\text{mo}} = \frac{2I_{\text{DSS}}}{V_P \vee}$	g_{mo}: g_m at V_{GS}=0 I_{DSS}: Drain saturation current at pinch-off V_P: Pinch-off voltage
$g_m = g_{\text{mo}}\left[1 - \frac{V_{\text{GS}}}{V_P}\right]$	g_m: Trans-conductance g_{mo}: g_m at V_{GS}=0

	V_{GS}: Gate to source voltage V_P: Pinch-off voltage
JFET Fixed Bias circuit:	
$A_v = -g_m(r_d \vee R_D)$	A_v : Voltage Gain g_m: Trans-conductance r_d: Dynamic drain resistance R_D: Drain Resistor
$Z_o = R_D \vee r_d$	Z_o: Output impedance R_D: Drain resistor r_d: Dynamic drain resistance
Self-Bias Configuration:	
$A_v = -g_m(r_d \vee R_D)$	A_v : Voltage Gain g_m: Trans-conductance r_d: Dynamic drain resistance R_D: Drain Resistor
$Z_o = R_D \vee r_d$	Z_o: Output impedance R_D: Drain resistor r_d: Dynamic drain resistance
JFET Self-Bias Configuration (Un-bypassed R_S):	
$Z_O = \frac{1 + g_m R_S + \frac{R_S}{r_d}}{1 + g_m R_S + \frac{R_S}{r_d} + \frac{R_D}{r_d}} R_D$	Z_o: Output impedance R_D: Drain resistor r_d: Dynamic drain resistance g_m: Trans-conductance R_S: Source resistor
$A_v = \frac{-g_m R_D}{1 + g_m R_S + \frac{R_D + R_S}{r_d}}$	A_v : Voltage Gain g_m: Trans-conductance r_d: Dynamic drain resistance R_D: Drain Resistor R_S: Source resistor
JFET Voltage Divider Configuration:	
$Z_i = R_1 \vee R_2$	Z_i: Input impedance R_1 & R_2: Resistors in the input circuit
$Z_o = r_d \vee R_D$	Z_o: Output impedance R_D: Drain resistor r_d: Dynamic drain resistance
$A_v = -g_m(r_d \vee R_D)$	A_v : Voltage Gain g_m: Trans-conductance r_d: Dynamic drain resistance R_D: Drain Resistor
JFET Common Gate Circuit:	
$Z_i = R_S \vee \frac{1}{g_m}$	Z_i: Input impedance g_m: Trans-conductance
$Z_O = r_d \|\| R_D$	Z_o: Output impedance R_D: Drain resistor r_d: Dynamic drain resistance
$A = \frac{\frac{R_D}{r_d} + g_m R_D}{1 + \frac{R_D}{r_d}}$	A_v : Voltage Gain g_m: Trans-conductance r_d: Dynamic drain resistance R_D: Drain Resistor

Enhancement MOSFET: Drain Feedback configuration	
$Z_i = \frac{R_F}{1 + g_m(r_d \vee R_D)}$	Z_i: Input impedance g_m: Trans-conductance r_d: Dynamic drain resistance R_D: Drain Resistor R_F: Feedback resistor
$Z_o = r_d \vee R_D$	Z_o: Output impedance R_D: Drain resistor r_d: Dynamic drain resistance
$A_v = -g_m(r_d \vee \lvert R_D \rvert \vee R_F)$	A_v : Voltage Gain g_m: Trans-conductance r_d: Dynamic drain resistance R_D: Drain Resistor R_F: Feedback resistor
Enhancement MOSFET: Voltage-divider configuration	
$Z_i = R_1 \vee R_2$	Z_i: Input impedance R_1 & R_2: Resistors in the input circuit
$Z_o = r_d \vee R_D$	Z_o: Output impedance R_D: Drain resistor r_d: Dynamic drain resistance
$A_v = -g_m(r_d \vee R_D)$	A_v : Voltage Gain g_m: Trans-conductance r_d: Dynamic drain resistance R_D: Drain Resistor
Frequency Response of amplifiers:	
$dB = 10\log_{10}\left(\frac{P_2}{P_1}\right)$	dB: gain in decibel P_1: Input power P_2: Output power
$f_L = \frac{1}{2\pi(R_S + R_i)C_S}$	f_L: Lower cut-off frequency R_S: Resistance of the signal source R_i: Input resistance C_S: Coupling capacitor in the input circuit

Characteristics	**Feedback Topology**			
	Voltage - Series	**Current - Series**	**Current - Shunt**	**Voltage - Shunt**
F.B signal X_f	Voltage	Voltage	Current	Current
Sampled Signal X_o	Voltage	Current	Current	Voltage
Signal Source	Thevenin	Thevenin	Norton	Norton
$\beta = X_f / X_o$	V_f / V_o	V_f / I_o	I_f / I_o	I_f / V_o
$A = X_o / X_e$	$A_v = V_o / V_e$	$G_M = I_o / V_e$	$A_I = I_o / I_i$	$R_M = V_o / I_i$
$D = 1 + \beta A$	$1 + \beta A_V$	$1 + \beta G_M$	$1 + \beta A_I$	$1 + \beta R_M$
A_f	A_V / D	G_M / D	A_i / D	R_M / D

R_{if}	R_i D	R_i D	R_i / D	R_i / D
R_{of}	R_o / (1+ β A_v)	R_o (1+ β G_m)	R_o (1+ β A_i)	R_o/(1+ β R_m)
$R'_{of} = R_{of} \parallel R_L$	R'_o / D	R'_o ((1+ β G_m)/D)	R'_o ((1+ β A_i)/D)	R'_o / D
$R'_O = R_o \parallel R_L$	$A_v = lim_{R_{L\to\infty}} A_V$	$G_m = lim_{R_{L\to 0}} G_M$	$A_i = lim_{R_{L\to 0}} A_I$	$R_m = lim_{R_{L\to\infty}} R_M$

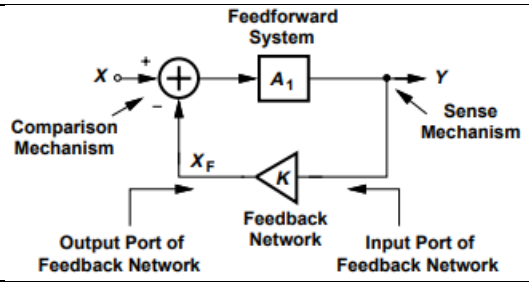
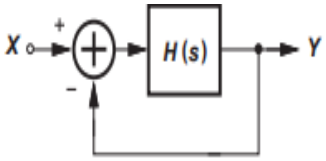
Oscillators:

BJT RC Phase shift oscillator	
$f_O = \frac{1}{2\pi \mathrm{RC}\sqrt{6}}$	f_O: frequency of oscillation R: Resistance in the feedback network C: Capacitance in the feedback network
Colpitts Oscillator	
$f_O = \frac{1}{2\pi\sqrt{\mathrm{LC_{eq}}}}$	f_O: frequency of oscillation C_{eq}: Equivalent capacitance L: Inductance in the feedback loop
Hartley Oscillator	
$f_O = \frac{1}{2\pi\sqrt{L_{\mathrm{eq}}C}}$	f_O: frequency of oscillation L_{eq}: Equivalent inductance C: Capacitance in the feedback loop
Crystal Oscillator	
$f_P = \frac{1}{2\pi\sqrt{\mathrm{LC}}}$ $f_P = \frac{1}{2\pi\sqrt{\mathrm{LC_{eq}}}}$	f_S: Series resonant frequency L: Inductance C: capacitance f_P: Parallel Resonant Frequency C_{eq}: Equivalent capacitance
Relaxation Oscillator	
$T = 2.303 R_E C_E \log_{10} \frac{1}{(1-\eta)}$	T: Time period R_E: Emitter resistor C_E: Emitter capacitor η: Intrinsic stand-off ratio of UJT

Power Amplifiers:

Parameter	Power Amplifier		
	Class -A	Class-B (Push-pull)	Class-C
Power Output	$P_O = \frac{V_{\mathrm{CEQ}} I_{\mathrm{CQ}}}{2}$	$P_{O(\max)} = \frac{1}{4} V_{\mathrm{CC}} i_{C(\mathrm{Sat})}$	$P_{O(\max)} = \frac{V_{\mathrm{CC}}^2}{2r_C}$
Efficiency (%)	$\eta = \frac{P_{a.c}}{P_{d.c}} \times 100$	$\eta = \frac{P}{P_{d.c}} \times 100$	$\eta = \frac{P_O}{P_i} \times 100$

Power Dissipation	$P_{D(max)} = 2P_{O(max)}$	$P_{D(max)} = \frac{1}{5} P_{O(max)}$	$P_D = \frac{V_{CE(Sat)} \times P_{O(max)}}{V_{CC}}$

Negative feedback Close loop Gain		$A_{1,closed} = \frac{A_1}{1+KA_1}$
Modified Input Impedaces of Negative feedback toplogies	Voltage - Voltage feedback amplifier: $R_{in,closed} = R_{in}(1+KA_V)$ Voltage – Current feedback amplifier: $R_{in,closed} = \frac{R_{in}}{(1+KR_O)}$ Current – Current feedback amplifier: $R_{in,closed} = \frac{R_{in}}{(1+KA_I)}$ Current – Voltage feedback amplifier: $R_{in,closed} = R_{in}(1+KG_m)$	
Modified Output Impedaces of Negative feedback toplogies	Voltage - Voltage feedback amplifier: $R_{out,\ closed} = \frac{R_{out}}{(1+KA_V)}$ Voltage – Current feedback amplifier: $R_{out,\ closed} = \frac{R_{out}}{(1+KR_O)}$ Current – Current feedback amplifier: $R_{out,\ closed} = R_{out}(1+KA_I)$ Current – Voltage feedback amplifier: $R_{out,\ closed} = R_{out}(1+KG_m)$	
Barkhausen Criteria for Oscillation		$\frac{Y}{X} = \frac{H(S)}{1+H(S)}$ $\lvert H(S)\rvert = 1$ $\angle H(S) = 180^0$