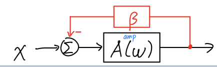
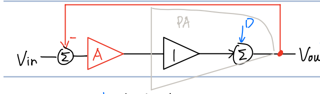
**Feedback**



$0<\beta\le 1$ (E. v. divider)

$y \stackrel{\because}{=} \frac{A}{1+A\beta}x \approx \frac{1}{\beta}x \quad G=\frac{1}{\beta}$

**E. distortion**



$V_{out} = V_{in} + \underbrace{\alpha_1 V_{in}^2 + \alpha_2 V_{in}^3 + \cdots}_{=D}$

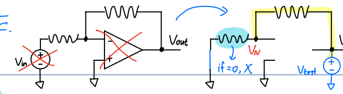
$V_{out} = D + A(V_{in} - V_{out})$

$V_{out} = \frac{D}{1+A} + \frac{A}{1+A}V_{in} \approx V_{in}$ if $A >> 1$

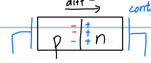
**Feedback check** 1. Shut down source

2. Remove opamp, connect $V_{out}$ to $V_{test}$

3. See if any of $V_{test}$ appears at $V_n$



**Diodes**

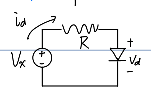


diff, dr, contact

eq. $i_d = I_s(e^{V_d/n\phi_t} - 1)$ (area, T; saturation $\sim 10^{-14}$)

$\phi_t \equiv \frac{kT}{|q|} = 26\text{ mV}$ (300K)

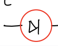
E.



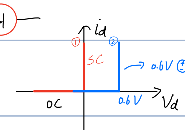
$\frac{V_x - V_d}{R} = i_d = I_s e^{V_d/n\phi_t}$

↳ transcendental :(

① $V_x \sim 100V \to V_d \approx 0$ in FB → ideal diode



② $V_x \sim 10V \to$ drop 0.6V, 0.3, 1.5 (Si, Ge, LED) → fixed-drop model



③ $V_x \sim 1V \to$ full Shockley a. numerical

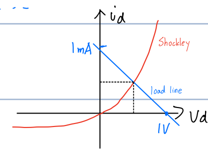
E. $R=100$, $V_x=1$ (1) guess $V_d = 0.5V$

(2) $i_d = \frac{1-0.5}{100} = 5mA$ (Ohm) (4) $i_d = 3mA$

(3) $V_d = 0.7V$ (Sch) (5) $V_d = 0.687V$ → ...

b. graphical Load line analysis E. R=1k, $V_x=1$

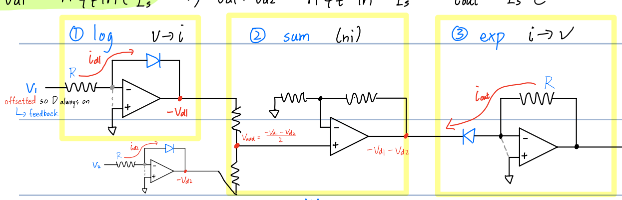
load line: $\frac{1-V_d}{1k} = i_d$ find intersection w/ Shockley



**Non-lin apps** 1. log

$V_{d1} = n\phi_t \ln(\frac{i_{d1}}{I_s}+1)$ (FB) $V_{d1}+V_{d2} = n\phi_t \ln\frac{i_{d1}i_{d2}}{I_s^2}$ $i_{out} = I_s e^{\frac{V_{d1}+V_{d2}}{n\phi_t}} = \frac{i_{d1}i_{d2}}{I_s}$

① log $V\to i$ ② sum (ni) ③ exp $i \to V$



$V_{out} = \frac{V_{in1}V_{in2}}{RI_s}$

offsetted so D always on ↳ feedback

Input: offsetted sin waves. E. $V_1$: 9k, $V_2$: 10k (AM) ⇒ $V_{out}$: 1k, 9k, 10k, 19k

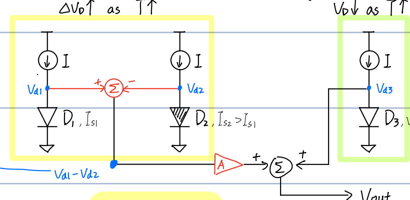
2. Temp $V_d = n\phi_t \ln\frac{i_d}{I_s}$ $V_d = V_{d_0} - 2\,mV/K\,(T-T_0)$

Bandgap ref. $T\uparrow \to V_0\downarrow$, but $\Delta V_0 \uparrow$, so we can weigh them and cancel

$\Delta V_0\uparrow$ as $T\uparrow$ $\quad V_0\downarrow$ as $T\uparrow$

$V_d = n\phi_t \ln\frac{I}{I_s}$

$V_{d1}-V_{d2} = n\frac{kT}{q}\ln\frac{I_{S2}}{I_{S1}}$



$V_{out} = V_{d3} + A(V_{d1} - V_{d2})$

$= V_{d_0} - 2\,mV/K\,(T-T_0) + A\,n\frac{kT}{q}\ln\frac{I_{s2}}{I_{s1}}$

$= V_{d_0} + 2\,mV/K\,T_0 + T(-2\,mV/K + \frac{Ank}{|q|}\ln\frac{I_{s2}}{I_{s1}})$ tune it

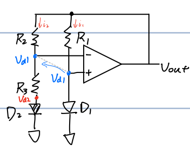
Kujik bandgap ⊖ feed, since ⊖ fed, ⊕ clipped only by $D_1$.

$V_p = V_N \to i_1 = i_2$ if $R_1 = R_2$

$V_{out} = i_2R_2 + V_{d1} = \frac{R_2}{R_3}(V_{d1}-V_{d2}) + V_{d1}$

$= \frac{R_2}{R_3}\left[\frac{nkT}{|q|}\ln\frac{i_1 I_{s2}}{i_2 I_{s1}}\right] + V_0 - 2mV/K\,(T-T_0)$

$= T\left[\frac{R_2}{R_3}\left(\frac{nk}{|q|}\ln\frac{I_{s2}}{I_{s1}}\right) - 2\,mV/K\right] + [V_0 + 2mV/K\,T_0]$ (~1.2V)

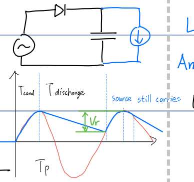


Choose $\frac{R_2}{R_3}$

$n = 1.752$ for 1N4148 $i_1 = \frac{V_{out} - V_{01}}{R_1} \stackrel{want}{=} 5mA \to R_1 = R_2 = 250\Omega \to R_3 = 26.2\Omega$ (make, more accurately)

Find slope of $V_{01}$ vs. T → recalculate $R_3 = 30.1\Omega$ (+V adjust)

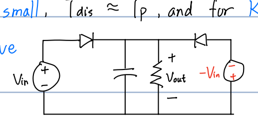
3. One-way DR: rectify RD: clip DC: peak det. DC+load: drop



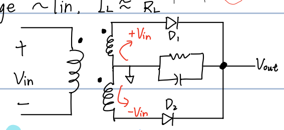
-Half wave + $I_{Load}$ (E. battery charger) → V↓ linear

$C V_R = \Delta Q = \int_{T_{dis}} I_L\,dt = T_{dis} I_L \to C = \frac{T_{dis}I_L}{V_R} \stackrel{worst}{=} \frac{T_p I_L}{V_R}$ (ripple; exp ~ lin)

if $V_R$ small, $T_{dis} \approx T_p$, and for R load, discharge ~ lin. $I_L \approx \frac{V_p}{R_L}$



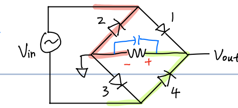
-Full-wave



C only need hold half as long $C = \frac{I_L T_p/2}{V_R}$

Can't breakdown $< 2V_{inp}$ (peak inverse voltage)

**Bridge**



$V_{in} > 0 \to D_{1,3}$ on

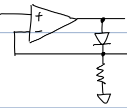
$V_{in} < 0 \to D_{2,4}$ on

$< 1 V_{inp}$

$I_D$ 1. avg. = avg $I_{load}$ (half) or $\frac{1}{2}$ avg $I_{load}$ (full) Long-term heating

2. peak $i_{peak} = C\frac{dV}{dt} + I_{load} \approx I_{load}(1 + 2\pi\sqrt{\frac{V_p}{2V_r}})$

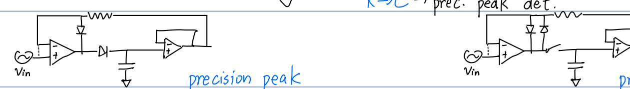
**Precision rect.** aka super diode



$V_{in} > 0$, no drop, $V_{out} = V_{in} = V_{OA} - V_D$

$V_{in} < 0 \to$ pulled down to 0 $V_{OA} = V_{SS}$

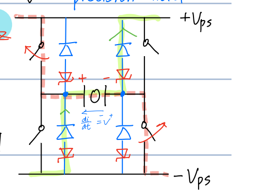
R→C → prec. peak det.



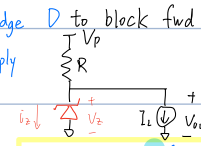
precision peak, sample hold

DC motor driver (inductive) Switch off → $V\uparrow = L\frac{di}{dt} = -2V_{ps} - 2V_D - 2V_Z$

↳ H-bridge D to block fwd current Z for more drop.



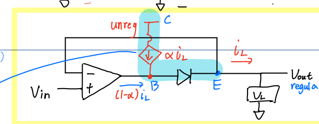
Power supply



$V_{out} = V_Z$

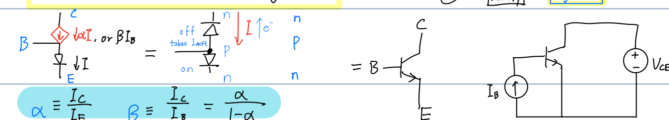
$I_L = \frac{V_p - V_Z}{R} - i_Z$, wasteful

Regulator (front peak detector)



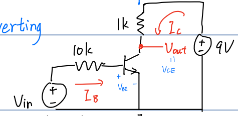
CCCS for more $i_L$ drive

BJT



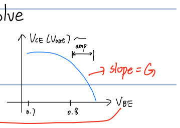
$\alpha \equiv \frac{I_C}{I_E} \quad \beta \equiv \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$

E. Inverting



$\begin{cases} I_C = \frac{9V - V_{CE}}{1k} & \text{(load line)} \\ I_C = f(V_{BE}, V_{CE}) & \text{(trans. curve)} \end{cases}$, inverting ⇒ Gsolve

Want to stay in active (E. bias)



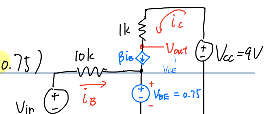
$I_B = \frac{V_{in} - V_{BE}}{10k} = \frac{I_C}{\beta = 100}$ $V_{in} = 100 I_C + V_{BE}$

$I_B \nearrow I_C$ (lin) $V_{BE} \nearrow I_C$ (exp), better play w/ $I_B$

Approx. $V_{BE} = 0.75V$

$V_{out} = V_{CC} - i_C R_2 = V_{CC} - (\beta\frac{V_{in} - 0.75}{R_1})R_2 = V_{CC} - \frac{R_2}{R_1}\beta(V_{in} - 0.75)$

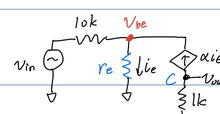
$V_{out} = \underbrace{V_{CC} - \frac{R_2}{R_1}\beta(V_{DC} - 0.75)}_{V_{BIAS}} - \underbrace{\frac{R_1}{R_2}\beta\Delta V}_{\Delta V_{out}} = -10\,\Delta V$



Small-sig $I_Q = I_s e^{V_Q/\phi_t}$ (quiescent)

$V_0 = V_Q + \Delta V \to i_0 = I_Q e^{\Delta V/\phi_t} = I_Q(1 + \frac{\Delta V}{\phi_t} + \cdots)$

$\Delta i = \frac{I_Q}{\phi_t}\Delta V \equiv \frac{\Delta V}{r_e}$ small-sig emitter $R \equiv \frac{\phi_t}{I_Q}$



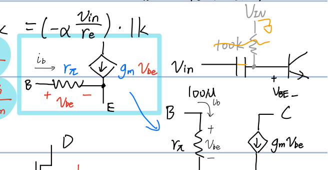
1. Find bias point (nonlin) with $V_{IN}$ (DC) $\xrightarrow{sim}$ $V_{out}$, $I_0$

2. Turn off $V_{IN}$, replace diode w/ $r_e = \frac{\phi_t}{I_E}$ $\quad \frac{V_{in} - i_e r_e}{10k} + \alpha i_e = i_e$ $\quad A_v \stackrel{\because}{=} -\frac{\alpha(1k)}{r_e + 10k(1-\alpha)}$

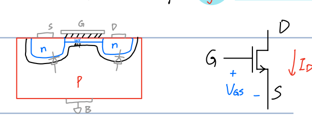
3. Add :) $V_{out} + v_{out}$ $\quad v_{out} = (-\alpha i_e)\cdot 1k = (-\alpha\frac{v_{in}}{r_e})\cdot 1k$

Hybrid π $\alpha i_e = i_c = g_m v_{be}$ $\quad g_m = \frac{\alpha}{r_e} = \frac{\alpha}{\phi_t/I_E} = \frac{I_C}{\phi_t}$

$i_e - i_c = i_b = \frac{v_{be}}{r_\pi}$ $\quad r_\pi = r_e\frac{i_e}{i_b} = r_e(1+\beta) = \frac{\beta}{g_m}$



MOS Sym. device



$V_{GS} = 0$ Cutoff

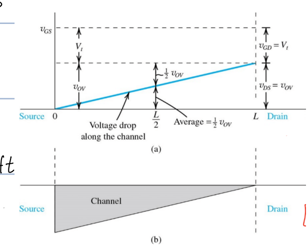
$0 < V_{GS} < V_T$ Subthreshold

$V_{GS} > V_T$ Lin. small $V_{DS} \to R$ controlled by $V_{GS}$

$V_{GS}\uparrow$ $g \propto V_{GS} - V_t$

Triode channel pinched, R↑. bad

Sat. $V_{DS} \ge V_{GS} - V_T$, all pinched, but $\mathcal{E}\uparrow$, $e^-$ drift



Sat. $i_D = \frac{1}{2}\mu C_{ox}\frac{W}{L}(V_{GS}-V_T)^2 (1 + \frac{V_{DS}}{V_A})$ for nonflat sat. ($=k'$)

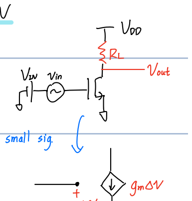
Lin. $i_D = V_{DS}[k'\frac{W}{L}(V_{GS}-V_T)]$ (VR)

Amplifier Need $V_{BIAS}$ for sat. (slope $V_{out}$ vs $V_{in}$), $V_{GS} = V_{BIAS} + \Delta V$

$i_D \stackrel{\because}{=} \underbrace{\frac{1}{2}k'\frac{W}{L}(V_{BIAS} - V_T)^2}_{=I_{BIAS}} + k'\frac{W}{L}(V_{BIAS} - V_T)\Delta V + \cdots\Delta V^2$

$\equiv I_{BIAS}$ region setup $\equiv g_m$, for amp. $= \sqrt{2k'\frac{W}{L}I_{BIAS}}$

$= I_{BIAS} + g_m\Delta V = \frac{1}{2}k'\frac{W}{L}V_{ov}^2 + g_m\Delta V$



$V_{out} = V_{DD} - \frac{1}{2}k'\frac{W}{L}V_{ov}^2 R_L$ $\quad v_{out} = -g_m v_{in} R_L$

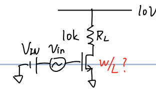
$\equiv V_{DD} - V_{DROP}$ $\quad \equiv -A_v v_{in}$

Design eq. $V_{ov} = \frac{2V_{DROP}}{|A_v|}$ $\quad (A_v = g_m R_L = k'\frac{W}{L}V_{ov})$

E. $V_T = 1V$, $k'\frac{W}{L} = 44.4\,mA/V^2$, $A_v = -20$, $V_{out}$ swing $= \pm 2V$, $V_{DD} = 10V$

Let $V_{out} = 5V \to V_{DROP} = 5V \to V_{ov} = \frac{2V_{DROP}}{|A_v|} = 0.5V \xrightarrow{+V_t} V_{GS} = 1.5V$ $\quad |A_v| \stackrel{\because}{=} g_m R_L \to R_L = 900\Omega$

E. Find $\frac{W}{L}$, given $A_v = 20$, swing $\pm 2V$, $k' = 30\,mA/V^2$, $V_T = 0.3V$

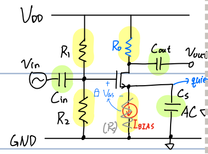


Choose $R_L = 10k$, $V_{DROP} = 5V \to I_D = 500\,\mu A$

$|A_v| = g_m R_L = \sqrt{2k' \frac{W}{L} I_D}\, R_L \longrightarrow \frac{W}{L} \doteq 133.3$

Safer to bias $I_D$, not $V_{GS}$ ($V_{OD}$), due to $\sqrt{\ }$

Bias: $I_{BIAS}$ pulls down $V_S$ until $V_{GS}$ is appropriate, indep. of $V_T$



E. $I_{BIAS} = R_S$ (variable). Given $V_T = 1V$, $k'\frac{W}{L} = 44.4\,mA/V^2$, $V_{DD} = 10V$

want $A_v = -20$, swing $= \pm 2V$, $V_{DROP} = 5V$ (3~7V), $f_{min} = 20\,Hz$

$\hookrightarrow V_{OD} = \frac{2V_{DROP}}{|A_v|} = 0.5V$, $V_{GS} = V_{OD} + V_T = 1.5V$, $R_D = \frac{|A_v|}{g_m \leftarrow k'\frac{W}{L}V_{OD}} \doteq 900\,\Omega$, $I_D = \frac{1}{2}k'\frac{W}{L}V_{OD}^2 = 5.55\,mA$

Swing: $V_{D,min} = 3V$, need $V_{GD} \le V_T$ for sat.

$V_{GS} = V_{GD} + V_{DS}$

$V_{OD} + \cancel{V_T} \ge \cancel{V_T} + V_{DS}$ (ss small-sig) $\longrightarrow V_{DS\,min} = V_{OD} = 0.5V$

Bias: Choose $V_S = 1V$ ($V_{GS}$) $\longrightarrow R_S = \frac{V_S}{I_D} = 180\,\Omega$

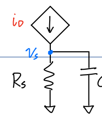
$V_G = 2.5V \longrightarrow$ make $R_1 = 75k$, $R_2 = 25k$ (10k ~ 100k)

Filter: HPF to block DC

$C_{in}$: $f_{in} = \frac{1}{2\pi C_{in}(R_1 \| R_2)} = \frac{f_{min}}{10} \longrightarrow C_1 \doteq 4.24\,\mu F$

$C_S$: $g_m(v_g - v_s) = i_D = v_s \frac{1 + sR_SC_S}{R_S}$ (classical approach)

$v_s = v_g \frac{g_m R_S}{1 + g_m R_S + sR_SC_S}$



corner at $1 + g_m R_S = \omega R_S C_S$, $C_S \doteq 2.2\,mF$ ($R_S$ only $180\,\Omega$)

$C_S$ will be much smaller if $R_S \uparrow$ ($C \leftrightarrows \omega$)

if no $C_S$, feedback at both AC/DC ($V_{gs}\uparrow \to i_d \uparrow \to v_s \uparrow \to v_{gs} \downarrow \to \cdots$)

$V_{out} = -(g_m v_{gs}) R_D$ $\qquad v_{gs} = v_{in} - g_m v_{gs} R_S = \frac{v_{in}}{1 + g_m R_S}$ (not present before)

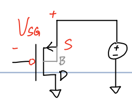
$A_v = \frac{v_{out}}{v_{in}} = \frac{-g_m R_D}{1 + g_m R_S}$ → neg. feedback, but improves distortion at same output swing

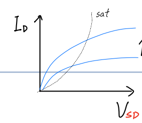
$\approx -\frac{R_D}{R_S}$ if $g_m R_S >> 1$

PMOS: pull G down for $I_D$

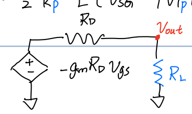
$I_D > 0$ for $V_{SG} > |V_{Tp}|$ and $V_{SD} > 0$

$I_D = \frac{1}{2}k_p' \frac{W}{L}(V_{SG} - |V_{Tp}|)^2$






Load

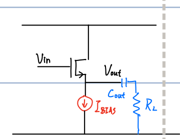


$|A_v| = g_m R_D \frac{R_L}{R_L + R_D}$

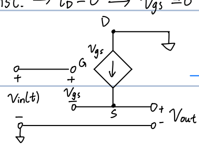
$= g_m(R_D \| R_L)$ (divided)

$\hookrightarrow$ Buffer (follower) (HW)

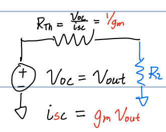
$I_D$ = const. $\overset{ss}{\to} i_D = 0 \to v_{gs} = 0 \to v_{out} = v_{in}$



ss.



Th.



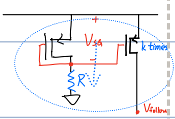
$V_L = V_{in} \frac{R_L}{R_L + 1/g_m}$ $\qquad 1/g_m \sim 10\,\Omega$, small

$\omega_{corner} = \frac{1}{C_{out}(R_L + 1/g_m)}$

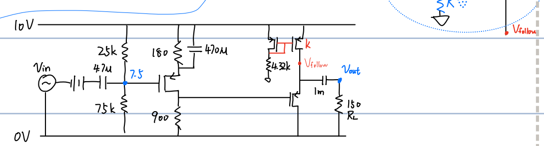
Make sure $I_D$ swing remains active ($I_{BIAS} \pm \frac{V_{out}}{R_L}$), else distorted

$I_{BIAS}$ setup ($V_{SG} = V_{SD} \to I_D$)

R just to set $V_{SG}$ for $k \times$ PMOS $\longrightarrow$ mirror



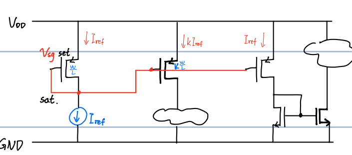
PMOS implementation



Current mirror: $I_{ref}$ to all analog cells

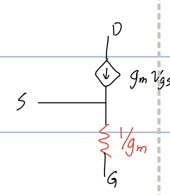
$I_{ref} \overset{pulls}{\longrightarrow} V_{sg} = V_{sg,others} \to I_{others}$

Need to ensure sat.



Alt ss. model (easier math)

$1/g_m$ cancels $\Diamond$, so $i_g$ remains 0.



| ss | DC | tot |
|---|---|---|
| $v_{gs}$ | $V_{GS}$ | $v_{GS}$ |

Diode: $i_D = I_S(e^{V_D/n\phi_t} - 1)$ ($I_S$: f(area, T), saturation, ~$10^{-14}$; $1 \le n \le 2$)

$\phi = \frac{kT}{|q|} = \frac{1.38E{-23}\,J/K \cdot 300K}{1.6E{-19}\,C} = 25.875\,mV$

$V_D = n\phi_t \ln\left(\frac{i_D}{I_S} \cancel{+1}\right)$

$V_{d1} - V_{d2} = n\frac{kT}{q} \ln \frac{I_{S2}\, I_{d1}}{I_{S1}\, I_{d2}}$

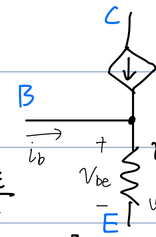
also $V_D = V_{D0} - 2m(T - T_0)$

rect: $C = \frac{I_L T_P\,(/2)}{V_{RIP}}$

BJT: $\alpha = \frac{I_C}{I_E} = \frac{\beta}{1+\beta}$ $\qquad \beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$

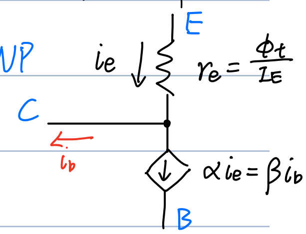
$V_{OUT} = V_{CC} - \frac{R_2}{R_1}\beta(\underbrace{V_{DC} - 0.75}_{V_{BIAS}}) - \underbrace{\frac{R_1}{R_2}\beta\,\Delta V}_{\Delta V_{out}}$

SS NPN



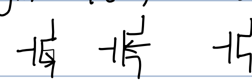

$r_e = \frac{\phi_t}{I_E}$

PNP

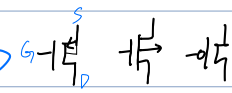



$\pi$: $g_m = \frac{I_C}{\phi_t}$, $r_\pi = \frac{\beta}{g_m}$

MOS: N



P



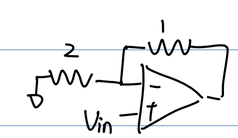
active: $V_{GS} - V_T > 0$ $\qquad V_{SG} - |V_{T,p}| > 0$

sat: $V_{DS} \ge V_{GS} - V_T$ $\qquad V_{SD} \ge V_{SG} - |V_{Tp}|$

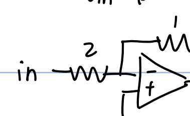
$i_D = \frac{1}{2}k'\frac{W}{L}(V_{GS} - V_T)^2$ ($A/V^2$)

$g_m = \sqrt{2k'\frac{W}{L}I_{BIAS}}$

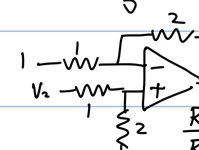
w/ load $|A_v| = g_m(R_D \| R_L)$



$1 + \frac{R_1}{R_2}$



$-\frac{R_1}{R_2}$



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

N, P (up, down?)

S/E may not be 0

$V_p = \sqrt{2}\, V_{rms}$