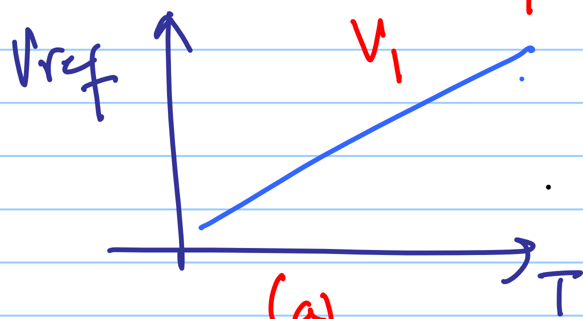
ECE 511: Lecture 27

Note Title 4/30/2015

Bandgap References: PVT-independent Reference

BMR were not temperature insensitive

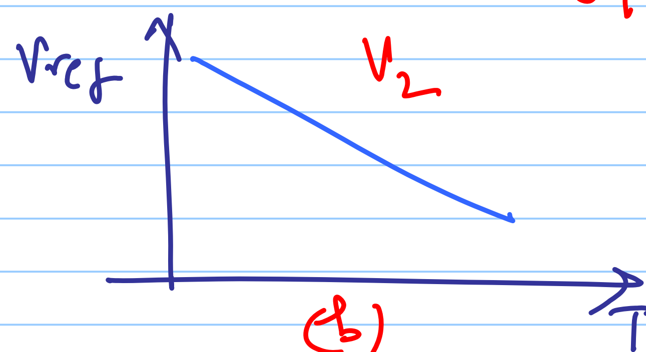
PTAT $\qquad \dfrac{\partial V_1}{\partial T} > 0$



(a)

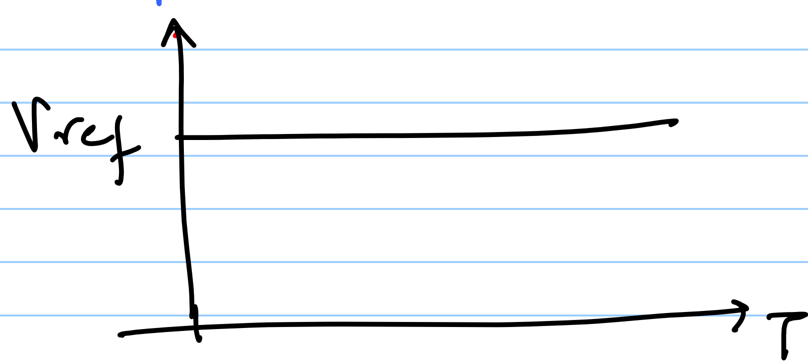
proportional to absolute temperature

CTAT $\qquad \dfrac{\partial V_2}{\partial T} < 0$



(b)

complementary to absolute temperature



Zero temperature coefficient

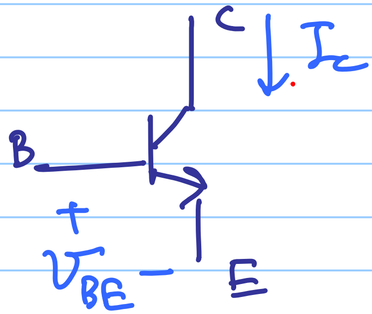
Zero TempCo (ZTC)

We can design a ZTC reference

$$V_{ref} = \alpha_1 \underset{\text{PTAT}}{V_1} + \alpha_2 \underset{\text{CTAT}}{V_2} \quad \text{(1)}$$

$$\frac{\partial V_{ref}}{\partial T} = \alpha_1 \frac{\partial V_1}{\partial T} + \alpha_2 \frac{\partial V_2}{\partial T} = 0 \quad \text{for some } \alpha_1, \alpha_2$$

①



$$I_c = I_s e^{\frac{V_{BE}}{\eta V_T}}$$

$$V_T = \frac{kT}{q} = 26\,mV$$

at
27°c
300 k

$$I_s \propto \mu\, kT \cdot n_i^2 \rightarrow ①$$

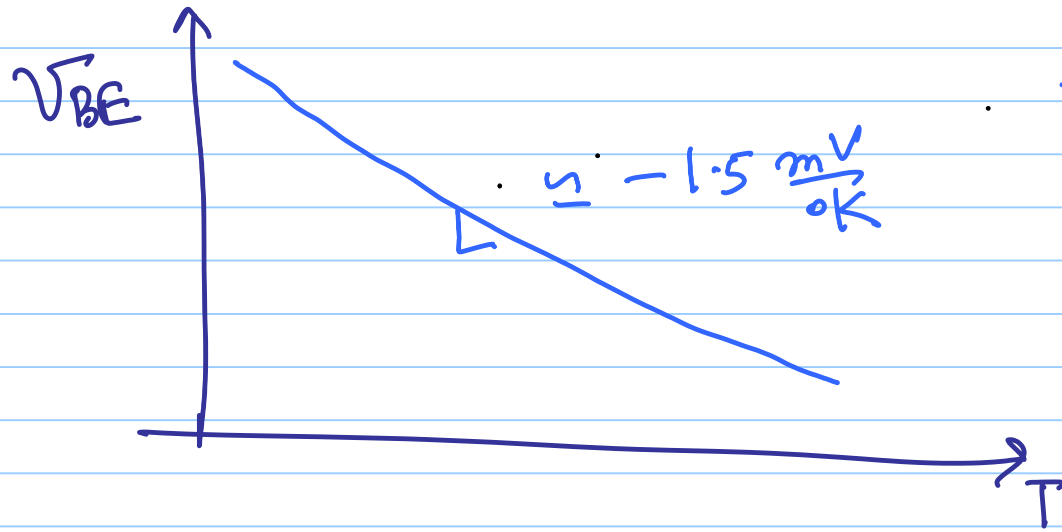
$$\mu \propto \mu_0 T^m, \quad m = -\frac{3}{2}$$

$$n_i^2 \propto T^3 e^{-E_g/kT}$$

$$I_s = b\, T^{(4+m)} e^{-E_g/kT} \rightarrow ②$$

$$V_{BE} = V_T \ln\left(\frac{I_c}{I_s}\right)$$

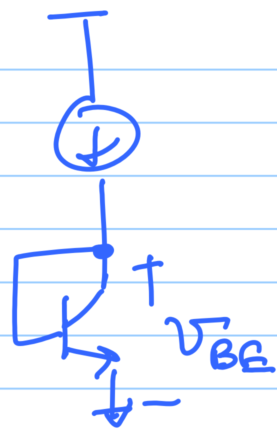
$$\frac{\partial V_{BE}}{\partial T} = \frac{V_{BE} - (4+m)V_T - E_g/q}{T}$$



$$\frac{\partial V_{BE}}{\partial T} \simeq -1.5 \ \frac{mV}{°K}$$

@ T = 300K

$V_{BE} = 0.65 - 0.78$



v_{BE} itself is a CTAT

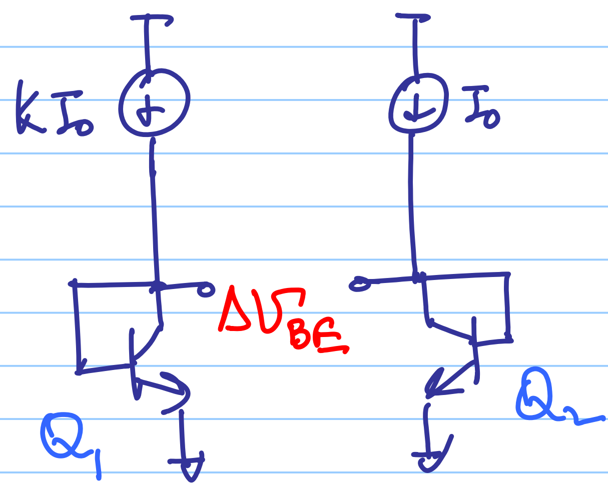
② PTAT

2 BJTs with unequal current

$V_{BE_1} \propto \ln(I_1/I_S)$

$V_{BE_2} \propto \ln(I_2/I_S)$

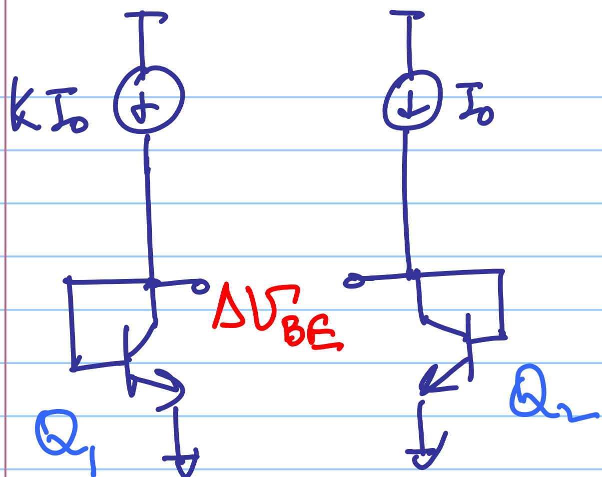
$V_{BE_1} - V_{BE_2} \propto \ln(K)$

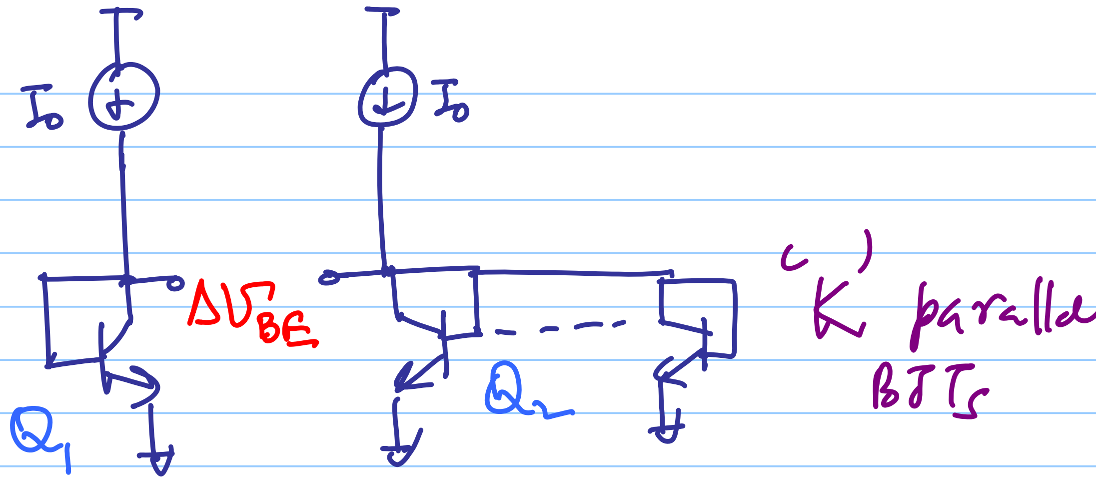


$$\Delta V_{BE} = V_T \ln\left(\frac{KI_o}{I_{S_1}}\right) - V_T \ln\left(\frac{I_o}{I_{S_2}}\right) \quad , \quad I_{S_1} = I_{S_2}$$

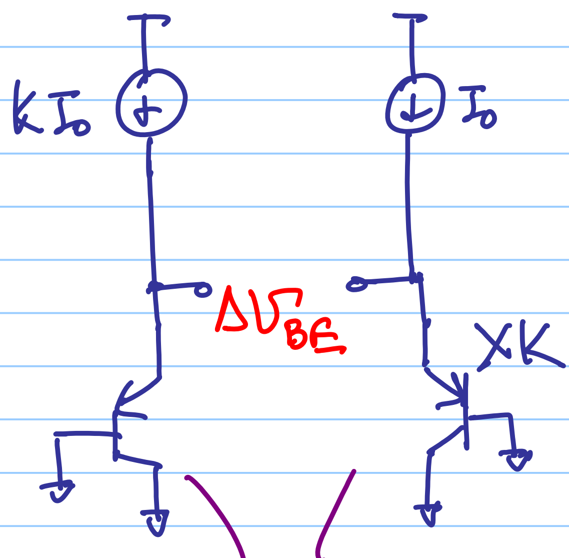
$$\Rightarrow \Delta V_{BE} = V_T \ln(K) = \frac{kT}{q} \ln(K) \qquad \text{PTAT}$$

$$\boxed{\frac{\partial \Delta V_{BE}}{\partial T} = \frac{k}{q} \ln(K)}$$





$$\Delta V_{BE} = V_T \ln\left(\frac{I_1}{I_2}\right) = V_T \ln\left(\frac{I_0}{I_0/K}\right) = V_T \ln(K)$$



parasitic pnp diods
in CMOS technology

Bandgap Reference

$$V_{ref} = \alpha_1 V_{BE} + \alpha_2 \overbrace{(V_T \ln K)}^{\Delta V_{BE}}$$

$$\frac{\partial V_{ref}}{\partial T} = 0 = \alpha_1 \frac{\partial V_{BE}}{\partial T} + \alpha_2 \left(\frac{k}{q} \ln K \right)$$

$$\alpha_2 \ln(K) = - \frac{\alpha_1 \cdot \overbrace{\left(\frac{\partial V_{BE}}{\partial T} \right)}^{-1.5 \text{ mV}/^\circ K}}{\underbrace{k/q}_{0.087 \text{ mV}/^\circ K}}$$

$$= \alpha_1 \times \frac{1.5 \text{ mV}/K}{0.087 \text{ mV}/K}$$

$$\Rightarrow \alpha_2 \ln K = 17.2\, \alpha_1$$

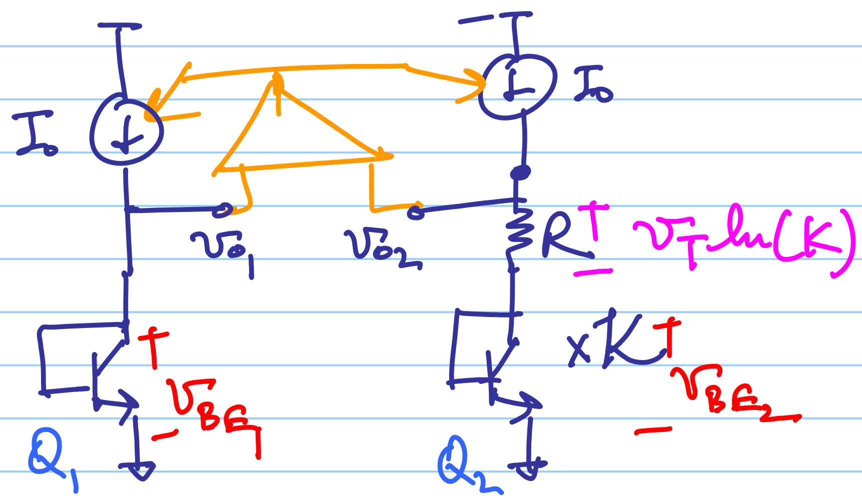
Choose $\alpha_1 = 1$

$$\Rightarrow \alpha_2 \ln(K) = 17.2$$

We have

$$V_{REF} = \alpha_1 \cdot V_{BE} + \alpha_2 \ln(K)\, V_T$$

$$= V_{BE} + 17.2\, V_T$$



If we can somehow make
$v_{o_1} = v_{o_2}$

$$v_{o_1} = v_{o_2} = v_{BE_1} = v_{BE_2} + I_o R$$

$$\Rightarrow I_o R = v_{BE_1} - v_{BE_2}$$
$$= v_T \ln(K)$$

$$\Rightarrow v_{o_2} = \underbrace{\alpha_1}_{1} \cdot \overbrace{v_{BE_2}}^{CTAT} + \underbrace{\alpha_2}_{1} \overbrace{v_T \ln(K)}^{PTAT}$$

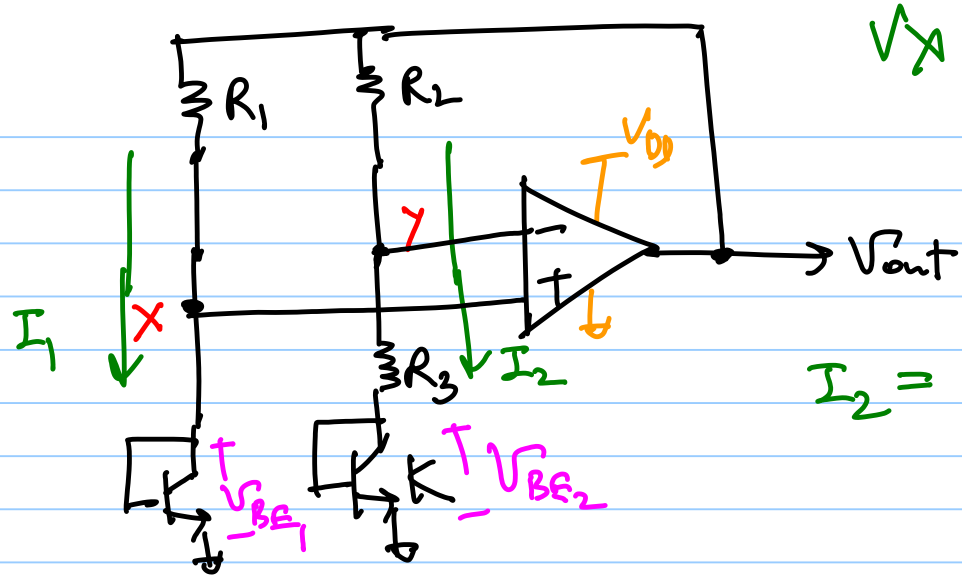
, here $\alpha_1 = \alpha_2 = 1$

for $\frac{\partial V_{o2}}{\partial T} = 0$, we need $\ln(K) = 17.2$

$K = e^{17.2}$ No!

$\Rightarrow$ We need a large α_2

Ex.



V_X & V_Y are equal

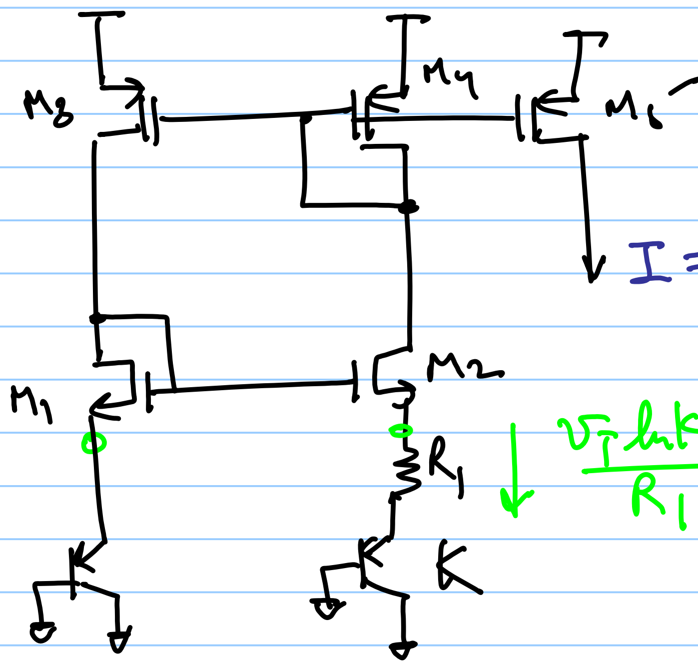
$$I_2 = \frac{V_{BE_1} - V_{BE_2}}{R_3} = \frac{V_T \ln(K)}{R_3}$$

$$V_{out} = V_{BE_2} + I_2 (R_3 + R_2)$$

$$= V_{BE_2} + \frac{V_T \ln(K)}{R_3}(R_3 + R_2)$$

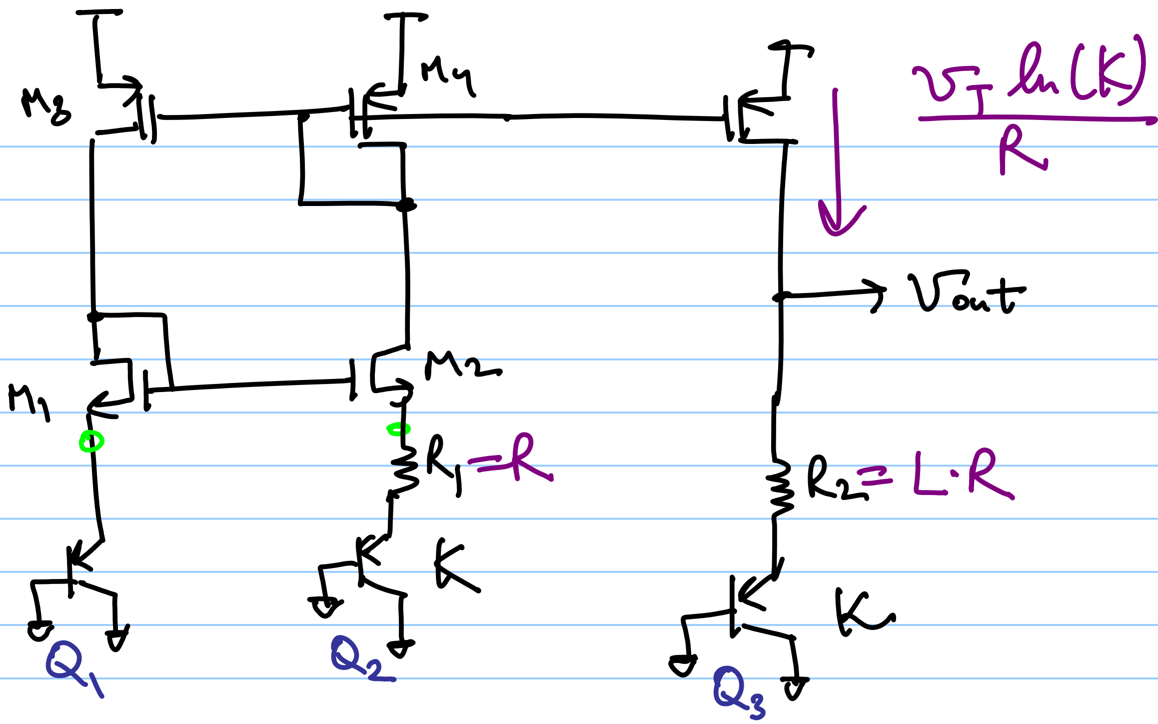
$$= \underbrace{v_{BE_2}}_{\alpha_1 = 1} + v_T \ln(k) \underbrace{\left(1 + \frac{R_2}{R_3}\right)}_{\alpha_2}$$

for example, for $k = 31$, $\frac{R_2}{R_3} = 4$



$I = \frac{PTAT}{R}$ type

$\frac{V_T \ln K}{R_1}$



$$V_{out} = V_{BE_3} + V_T \ln(K) \cdot L \quad \alpha_2$$

$$L \cdot \ln(K) = 17.2$$

choose any $\{L, K\}$

Ex.

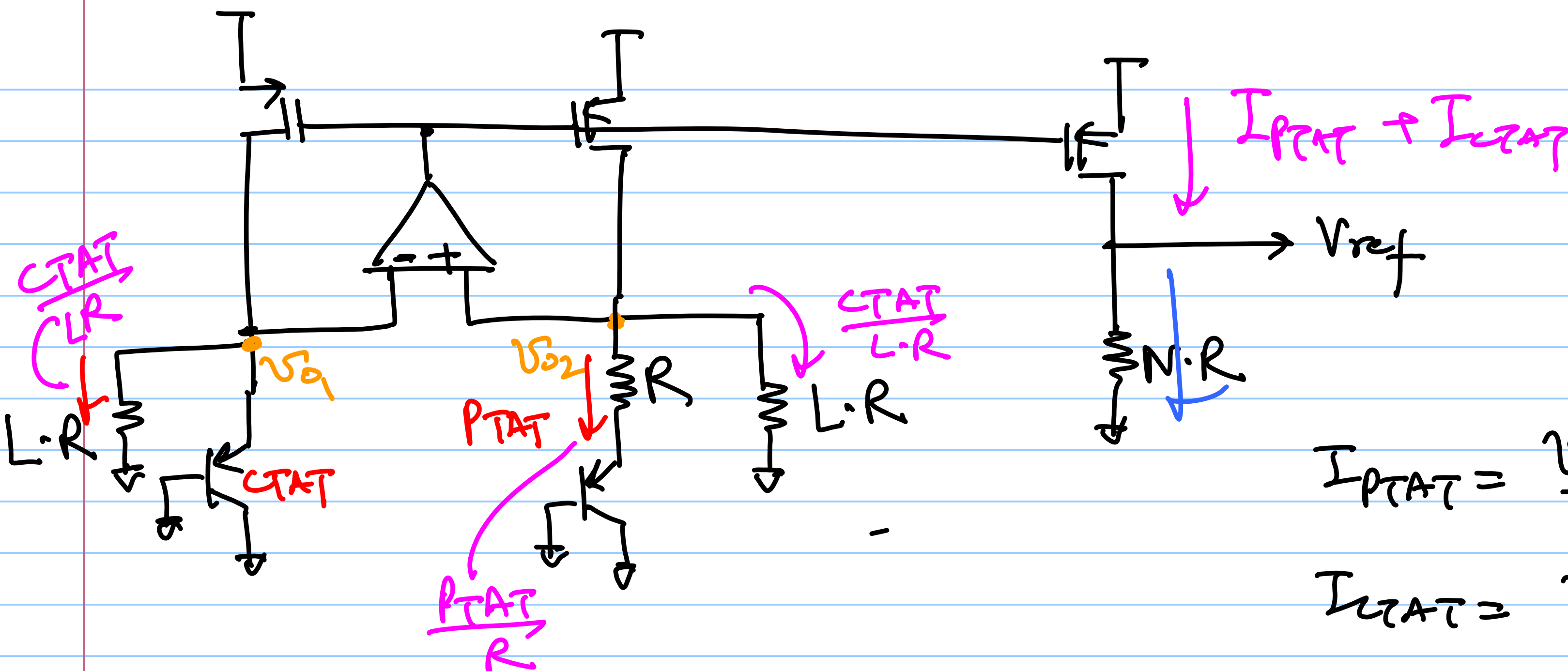
$K = 8$ (select) $n = 1$

$$L = \frac{\left|\left(\frac{\partial V_{BE}}{\partial T}\right)\right|}{\ln(K)\left(\frac{\partial V_T}{\partial T}\right)}$$

$$= \frac{1.8m}{0.087m \ln(8)} = 8.4834$$

$$V_{ref} = V_{BE_3} + L \cdot V_T \ln(K) \simeq 1.25V$$

ratio of R



$$I_{PTAT} = \frac{V_T \ln K}{R}$$

$$I_{CTAT} = \frac{V_{BE_1}}{L \cdot R}$$

$$V_{ref} = (I_{PTAT} + I_{CTAT}) \cdot N \cdot R$$

$$= \left(\frac{V_T \ln K}{\cancel{R}} + \frac{V_{BE_1}}{L \cdot \cancel{R}} \right) \cdot N \cdot \cancel{R}$$

$$= \underbrace{(N)}_{\alpha_2} V_T \ln(K) + \underbrace{\left(\frac{N}{L}\right)}_{\alpha_1} V_{BE_1}$$

$$\frac{\partial V_{ref}}{\partial T} = N \ln(K) \left(\frac{k}{q}\right) + \frac{N}{L} \left(\frac{\partial V_{BE}}{\partial T} \right) = 0$$

$$N \left[\frac{k}{q} \ln K + \frac{1}{L} \cdot \left(-1.5 \frac{mV}{K} \right) \right] = 0$$

independant of N

$$L = \frac{1.8}{\ln(K)\cdot 0.0085} \leftarrow \text{doesn't depend upon } N$$

Ex. $K = 8 \Rightarrow L = 9.41$

$$V_{ref} = V_T \ln K \cdot N + \frac{N}{L}\cdot V_{BE_1}$$

$$N = \frac{V_{ref}}{V_T \ln(K) + \frac{V_{BE_1}}{L}} \quad V_{BE_1} \to 0.7$$

for $V_{ref} = 0.5V \Rightarrow N = \frac{0.8}{0.052 + \frac{0.7}{9.41}} = 3.91$

low-V_{DD} BGR

Why Bandgap ?

$$V_{REF} = V_{BE} + V_T \ln(K)$$

for $\dfrac{\partial V_{REF}}{\partial T} = 0$

⋮

$$\Rightarrow V_{ref} = \frac{E_g}{q} + (4+m) V_T$$

as $T \to 0$

$V_{ref} \to \dfrac{E_g}{q} \leftarrow$ Bandgap Voltage $= 1.12V$