ECEN474/704: (Analog) VLSI Circuit Design
Spring 2018

Lecture 17: Bandgap Reference

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Announcements

- Project Report Due May 1
  - Email it to me by 5PM
- Exam 3 is on May 3
  - 3PM-5PM
  - Closed book w/ one standard note sheet
  - 8.5”x11” front & back
  - Bring your calculator
  - Covers material through Output Stages Lecture
  - Previous years’ exam 3s are posted on the website for reference

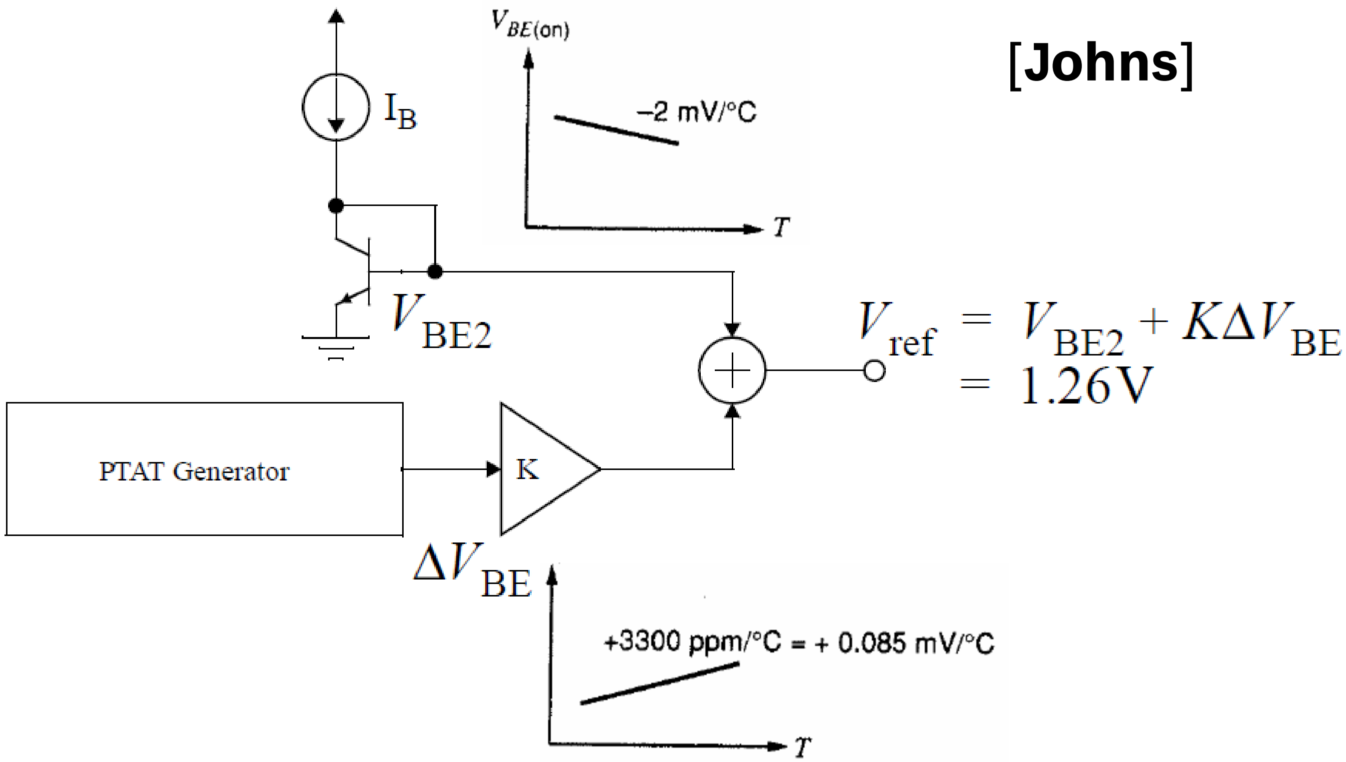
Agenda

- Bandgap Reference
  - Motivation and general concept
  - Generation of NTAT and PTAT voltages
  - CMOS bandgap references

Stable References for Analog Circuits

- Analog circuits require bias currents that are stable over process, voltage, and temperature for proper operation
- The most popular circuit used to generate a stable reference is a "Bandgap Reference"
- A Bandgap Reference Circuit generates a voltage that is very stable over temperature
  - This stable voltage can be used to generate a reference current stable over process, voltage, and temperature

Bandgap Voltage Reference Concept



[Johns]

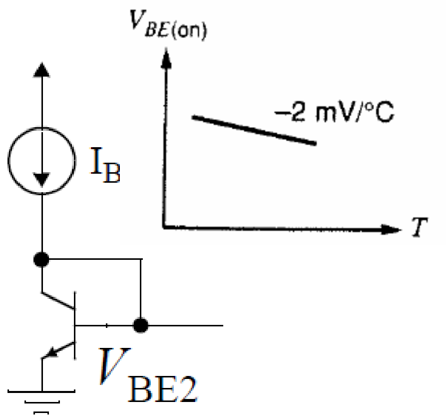
- V_{BE} has a negative temperature coefficient
- ΔV_{BE} has a positive temperature coefficient
- Add V_{BE} and ΔV_{BE} scaled by K for an output voltage with near zero temperature coefficient

Base-Emitter Voltage (V_{BE}) Temperature Coefficient (NTAT)

$$I_C = I_s e^{\frac{V_{BE}}{(kT/q)}} = A_E J_C$$

where A_E is the base - emitter junction area and J_C is the collector current density

It can be shown that



[**Johns**]

$$V_{BE} = V_{G0}\left(1 - \frac{T}{T_0}\right) + V_{BE0}\frac{T}{T_0} + \frac{mkT}{q}\ln\left(\frac{T_0}{T}\right) + \frac{kT}{q}\ln\left(\frac{J_C}{J_{C0}}\right)$$

where V_{G0} is the silicon bandgap voltage at 0°K (1.206V)

T_0 is the reference temperature at which the

reference base - emitter voltage, V_{BE0}, and current density, J_{C0}, are taken

m is a constant (3.2)

- For a constant I_C, V_{BE} has a **negative-to-absolute-temperature (NTAT)** coefficient of approximately -2mV/°K

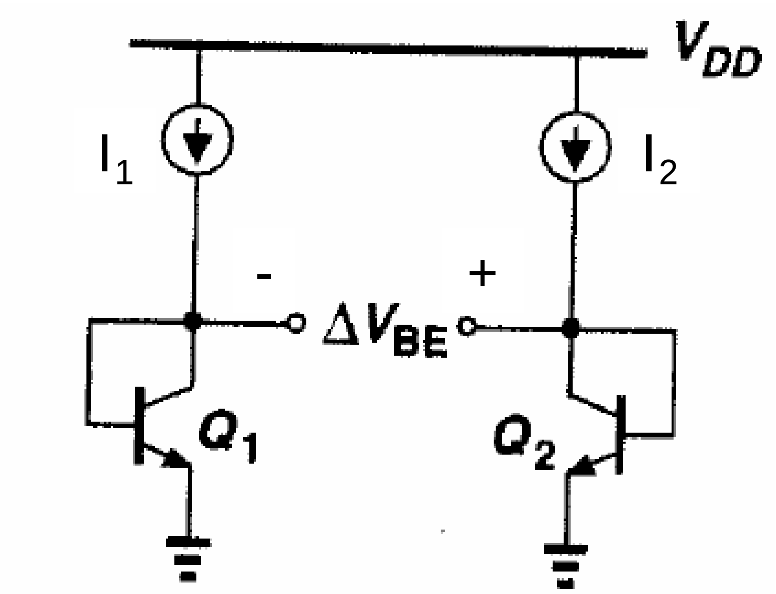
ΔV_{BE} Temperature Coefficient (PTAT)

$$I_C = A_E J_C$$

Two base-emitter junctions biased at different current densities, J_1 and J_2, will have different base-emitter voltage

$$\Delta V_{BE} = \frac{kT}{q} \ln\left(\frac{J_2}{J_1}\right)$$

[Razavi]



- The difference between the two junction voltages is **proportional-to-absolute-temperature (PTAT)**

Bandgap Reference Voltage

Adding an NTAT V_{BE} from Q2 and K times the PTAT ΔV_{BE}

$$V_{ref} = V_{BE2} + K\Delta V_{BE} = V_{G0}\left(1-\frac{T}{T_0}\right) + V_{BE0_2}\frac{T}{T_0} + \frac{mkT}{q}\ln\left(\frac{T_0}{T}\right) + \frac{kT}{q}\ln\left(\frac{J_{C_2}}{J_{C0_2}}\right) + K\frac{kT}{q}\ln\left(\frac{J_2}{J_1}\right)$$

Assuming that the junction currents are PTAT

(this will be shown to be true in the Bandgap circuits)

$$\frac{J_i}{J_{0_i}} = \frac{T}{T_0}$$

$$V_{ref} = V_{G0} + \frac{T}{T_0}\left(V_{BE0_2} - V_{G0}\right) + (m-1)\frac{kT}{q}\ln\left(\frac{T_0}{T}\right) + K\frac{kT}{q}\ln\left(\frac{J_2}{J_1}\right)$$

At $T = T_0$**,** $\quad V_{ref} = V_{BE0_2} + K\frac{kT}{q}\ln\left(\frac{J_2}{J_1}\right)$

Bandgap Reference Voltage

We desire V_{ref} to be "flat", i.e. have zero temperature coefficient at T_0

$$\frac{\partial V_{ref}}{\partial T} = \frac{1}{T_0}\left(V_{BE0_2} - V_{G0}\right) + (m-1)\frac{k}{q}\left[\ln\left(\frac{T_0}{T}\right) - 1\right] + K\frac{k}{q}\ln\left(\frac{J_2}{J_1}\right)$$

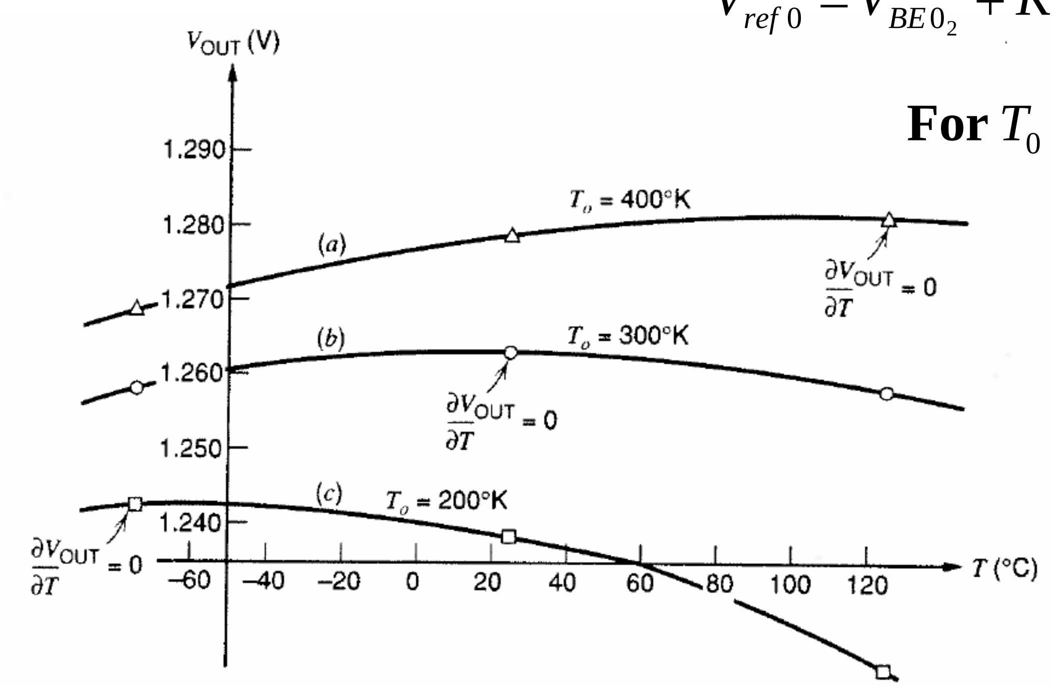
$$\left.\frac{\partial V_{ref}}{\partial T}\right|_{T=T_0} = \frac{1}{T_0}\left(V_{BE0_2} - V_{G0}\right) - (m-1)\frac{k}{q} + K\frac{k}{q}\ln\left(\frac{J_2}{J_1}\right) = 0$$

[Gray]

$$V_{ref\,0} = V_{BE0_2} + K\frac{kT_0}{q}\ln\left(\frac{J_2}{J_1}\right) = V_{G0} + (m-1)\frac{kT_0}{q}$$

For $T_0 = 300°$K and $m = 3.2$

$$V_{ref\,0} \cong 1.26V$$



Setting K Value

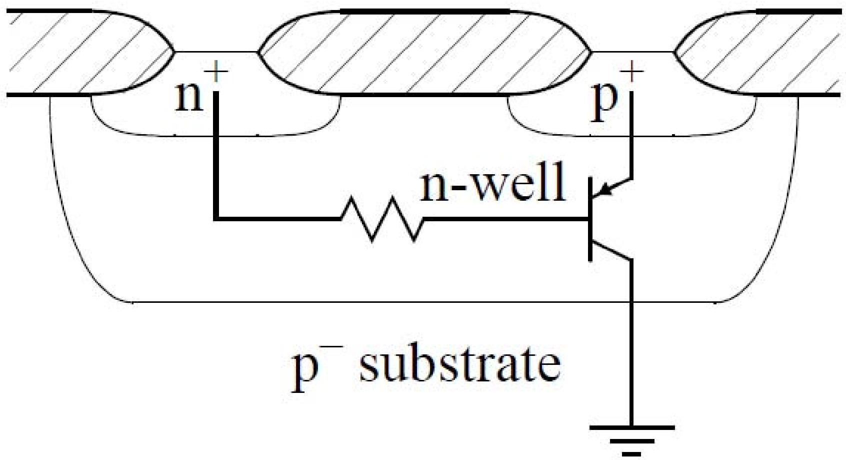
$$V_{ref\,0} = V_{BE0_2} + K\frac{kT_0}{q}\ln\left(\frac{J_2}{J_1}\right) = V_{G0} + (m-1)\frac{kT_0}{q} = 1.26V$$

$$K = \frac{V_{G0} + (m-1)\frac{kT_0}{q} - V_{BE0_2}}{\frac{kT_0}{q}\ln\left(\frac{J_2}{J_1}\right)} = \frac{1.26V - V_{BE0_2}}{(25.9mV)\ln\left(\frac{J_2}{J_1}\right)}$$

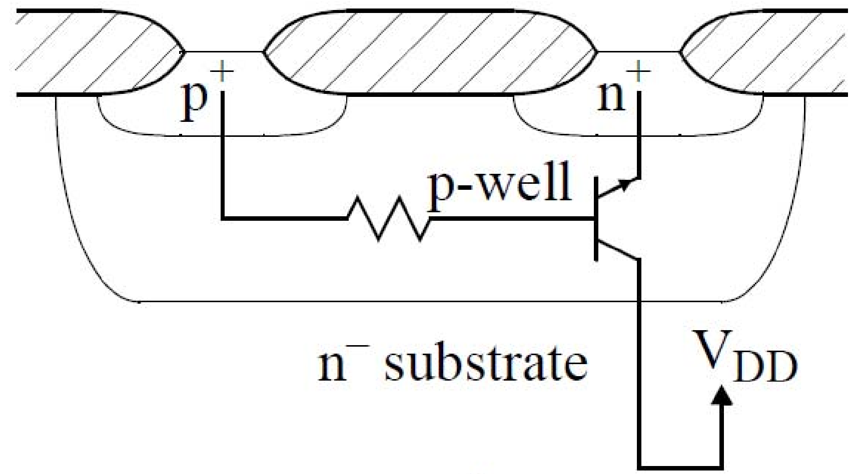
- The precise value of K is often set by "trimming" at wafer-level testing

CMOS Vertical BJTs

[**Johns**]



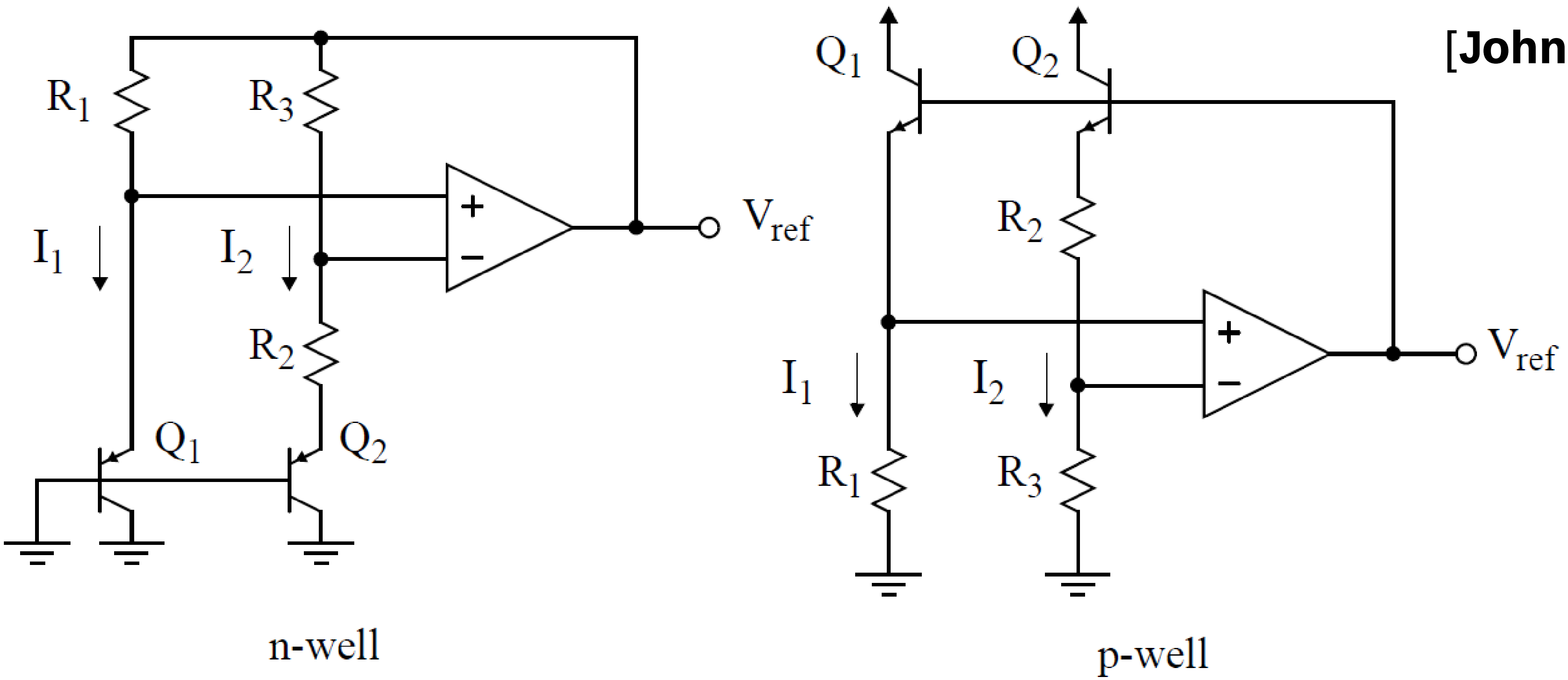
n-well



p-well

CMOS Bandgap Reference Circuits

[Johns]



CMOS Bandgap Reference

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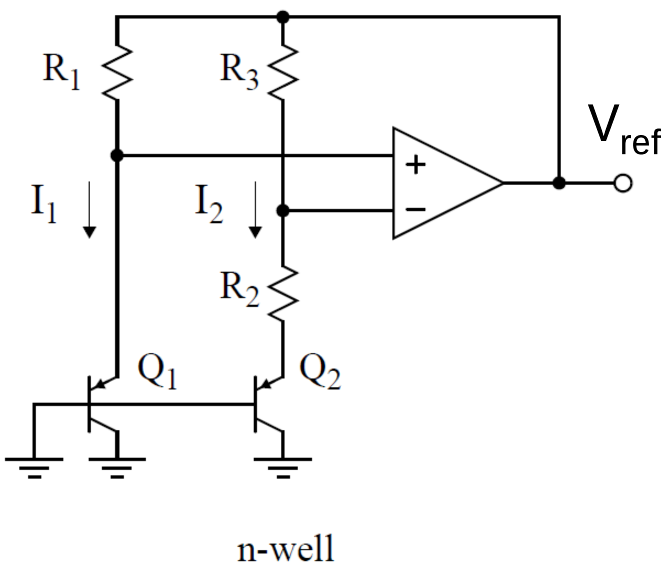


$$V_{ref} = V_{EB1} + V_{R1}$$

Assuming the opamp has high gain and forces a "virtual-short" of its two input voltages

$$V_{R2} = V_{EB1} - V_{EB2} = \Delta V_{EB}$$

As the same current I_2 flows through both R_2 and R_3

$$V_{R3} = \frac{R_3}{R_2} V_{R2} = \frac{R_3}{R_2} \Delta V_{EB}$$

For the Bandgap Reference Circuit : $K = \frac{R_3}{R_2}$

$$V_{ref} = V_{EB1} + V_{R3} = V_{EB1} + \frac{R_3}{R_2} \Delta V_{EB}$$

$$\Delta V_{EB} = V_{EB1} - V_{EB2} = \frac{kT}{q} \ln\left(\frac{J_1}{J_2}\right)$$

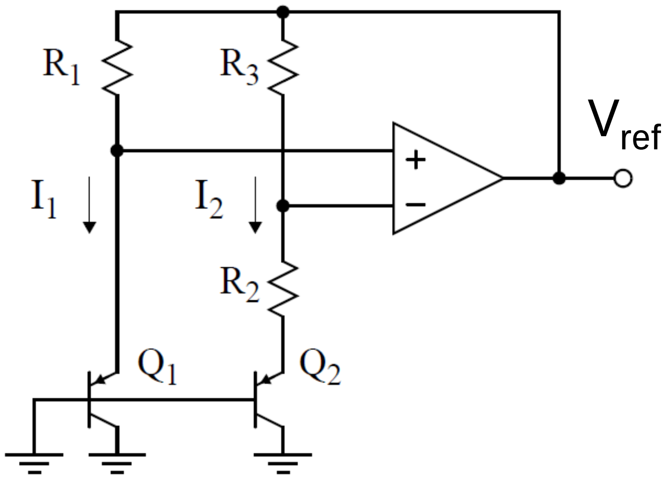
Assuming that the two bipolar transistors have the same base-emitter junction area

$$\frac{J_1}{J_2} = \frac{I_1}{I_2} = \left(\frac{V_{ref} - V_{EB1}}{R_1}\right)\left(\frac{R_3}{V_{ref} - V_{EB1}}\right) = \frac{R_3}{R_1}$$

$$V_{ref} = V_{EB1} + \frac{R_3}{R_2} \Delta V_{EB} = V_{EB1} + \frac{R_3}{R_2} \frac{kT}{q} \ln\left(\frac{R_3}{R_1}\right)$$

CMOS Bandgap Reference Example

[Johns]



Assume that at $T = 300°K$ that $V_{EB0_1} = 0.65V$ at $I_1 = 80\mu A$

The pnp transistors are the same size and $\frac{J_1}{J_2} = 10$

We desire that the output voltage be 1.26V at $T = 300°K$

$$V_{R1} = V_{ref0} - V_{EB0_1} = 1.26V - 0.65V = 0.61V$$

$$R_1 = \frac{V_{R1}}{I_1} = \frac{0.61V}{80\mu A} = 7.63k\Omega$$

$$R_3 = \frac{V_{R3}}{I_2} = \frac{0.61V}{8\mu A} = 76.3k\Omega$$

To find R_2, we find K to be

$$K = \frac{1.26V - V_{EB0_1}}{(25.9mV)\ln\left(\frac{J_1}{J_2}\right)} = \frac{1.26V - 0.65V}{(25.9mV)\ln(10)} = 10.2$$

$$R_2 = \frac{R_3}{K} = 7.48k\Omega$$

Next Time

- Exam 3 review