# E151 Lecture 15 – References

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## Disclaimer

These are notes for Prof. Spencer to give the lecture, they were not intended as a reference for students. Students asked for them anyway, so I'm putting them up as a courtesy. Remember that they are not intended as a substitute for attending lecture.

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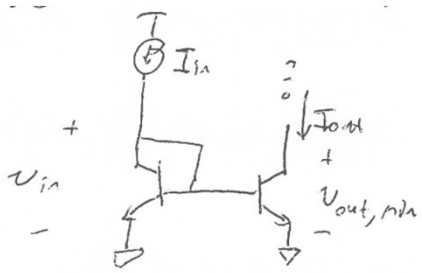
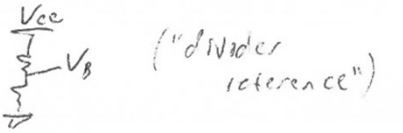
# How Do We Make Current Sources in Mirrors?




("diode reference")

- Need analysis tools to measure "how good" V or I reference is
- References need to be supply and temperature invariant (PVT is big)

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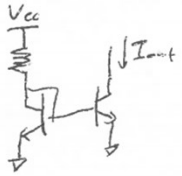
# Measure Quality of Reference with Sensitivity

Cadence sensitivity

$$S^{\gamma(x)}_{\text{to } x} \equiv S^{\gamma}_{x} \equiv \lim_{\Delta x \to 0} \frac{\Delta\gamma/\gamma}{\Delta x/x} = \frac{x}{\gamma}\frac{\partial \gamma}{\partial x}$$

← fractional change of $\gamma$ w/r/t $x$

eg: divider reference in simple mirror



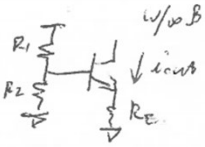

$$S^{I_{out}}_{V_{cc}} = \frac{V_{cc}}{I_{out}}\frac{\partial}{\partial V_{cc}}\left[\left(\frac{\beta}{\beta+2}\right)\cdot\left(\frac{V_{cc}-V_{be,on}}{R}\right)\right]$$

$$= \frac{\beta}{\beta+2}\cdot\frac{V_{cc}}{R}$$

$$\left(\frac{\beta}{\beta+2}\right)\left(\frac{V_{cc}-V_{be,on}}{R}\right)$$

$$= 1\Big/\left(1-\frac{V_{be,on}}{V_{cc}}\right) \approx 1$$ very sensitive!

you try




$S^{I_{out}}_{V_{cc}}$ =

$$I_{out} = \left(\frac{R_2}{R_1+R_2}V_{cc} - V_{be,on}\right)\cdot\frac{1}{R_E}$$

$$\frac{\partial I_{out}}{\partial V_{cc}} = \frac{R_2}{R_E}\cdot\frac{1}{R_1+R_2}$$

$$S^{I_{out}}_{V_{cc}} = \frac{1}{\left(1-\left(1+\frac{R_1}{R_2}\right)\frac{V_{be,on}}{V_{cc}}\right)} \approx 1$$

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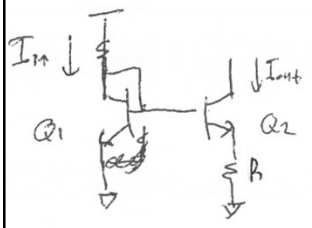
# "Widlar Current Source" Reference if Time




Interested in $I_{out}(I_{in})$

$$V_{be1} = V_{be2} + I_{out} R \cdot \frac{\beta}{\beta+1}$$

$$I_{S1} e^{V_{be1}/\phi_T} = i_{C1} \rightarrow V_{be1} = \phi_T \ln \frac{i_{C1}}{I_{S1}}$$

$$\phi_T \ln \frac{I_{in}}{I_{out}} \approx I_{out} R$$

- Note can't assume 0.7V there
- Need on $1/\beta$ to, $V_{be}$ (busy last lecture)

- Logarithmic compression of Iin, so called a reference

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# "Widlar Current Source" Reference if Time

- Sensitivity w/ 1mA and 1k this is a factor of 40 better

$$\text{Sensitivity} \sim \phi_T \frac{\partial}{\partial V_{cc}} \ln \frac{I_{in}}{I_{out}} = R \frac{\partial I_{out}}{\partial V_{cc}}$$

$$\phi_T \left( \frac{1}{I_{out}} \frac{\partial I_{in}}{\partial V_{cc}} - \frac{I_{in}}{I_{out}^2} \frac{\partial I_{out}}{\partial V_{cc}} \right) = R \frac{\partial I_{out}}{\partial V_{cc}}$$

$$\frac{\partial I_{out}}{\partial V_{cc}} = \left( \frac{1}{1 + \frac{I_{out} R}{\phi_T}} \right) \cdot \frac{I_{out}}{I_{in}} \cdot \frac{\partial I_{in}}{\partial V_{cc}}$$

$$S_{V_{cc}}^{I_{out}} = \frac{V_{cc}}{I_{out}} \cdot \frac{\partial I_{out}}{\partial V_{cc}} = \left( \frac{1}{1 + I_{out} R/\phi_T} \right) \cdot S_{V_{cc}}^{I_{in}} \approx \left( \frac{1}{1 + \frac{I_{out} R}{\phi_T}} \right)$$

($S_{V_{cc}}^{I_{in}} \approx 1$)

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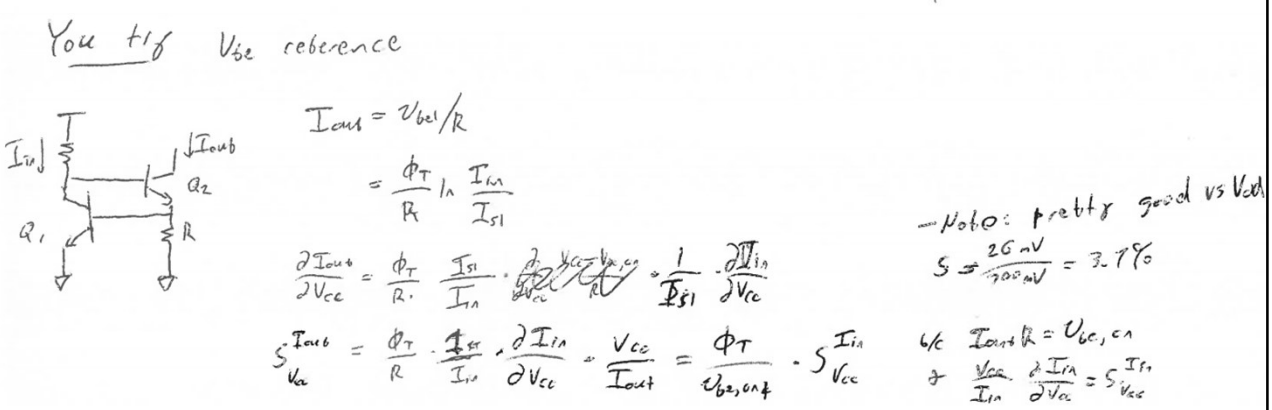
# Vbe Reference if Time




- I like this one, easy to implement, easy to analyze, good vs. supply

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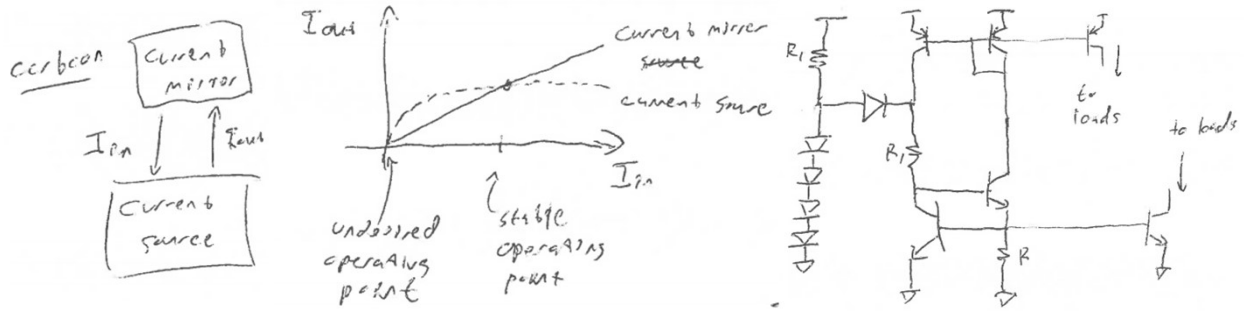
# Self-Biasing for Supply Insensitivity




- Get away from dropping Vcc over R … big sensitivity benefit
- Need startup circuit because undesired stable point (eg: 4Vbe vs. 3)
- Want startup circuits to shut themselves off (eg: rev. bias b/c of Rx)

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# Temperature Sensitivity

$$TC^{I_{out}} = \frac{1}{I_{out}} \frac{\partial I_{out}}{\partial T}$$

- Model w/ temperature coefficient (sensitivity to temp, % change/deg)
- Big issues: Resistors (+1100 ppm/C), Vbe (-2mV/C), $\phi_T$ (3300 ppm/C)
- Cancel OK in Widlar, bad issue in Vbe, assorted self-bias tricks
- Sometimes need reference V constant w/ both supply and temp (eg: regulators) → Band Gap

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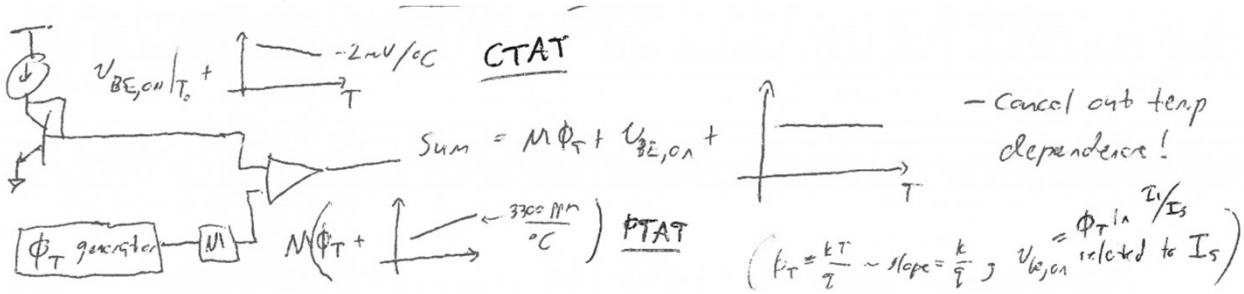
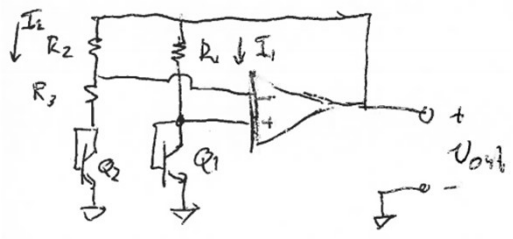
# Band Gap Reference




- Very literal implementation →

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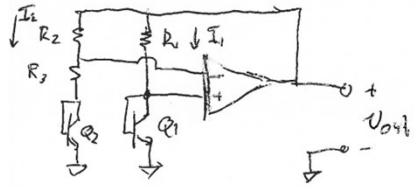


- op-amp forces $V_{R1} = V_{R2}$
- so $\frac{I_1}{I_2} = \frac{R_2}{R_1}$
- $\phi_T$ generating cir. can get it from $\Delta V_{be}$
- $V_{R3} = \underbrace{V_{be1} - V_{be2}}_{\Delta V_{be}} = \phi_T \ln \frac{I_1}{I_{S1}} - \phi_T \ln \frac{I_2}{I_{S2}} = \phi_T \ln \frac{R_2}{R_1} \frac{I_{S2}}{I_{S1}}$
- same current in $R_2$ & $R_3$, so $V_{R2} = \frac{R_2}{R_3} V_{R3}$

Finally, do KVL, $V_{out} = V_{be2} + V_{R2} + V_{R3}$

$= V_{be2} + \left(1 + \frac{R_2}{R_3}\right) \phi_T \ln \frac{R_2}{R_1} \frac{I_{S2}}{I_{S1}}$

$= V_{be2} + M \phi_T$ where $M = \left(1 + \frac{R_2}{R_3}\right) \ln \frac{R_2}{R_1} \frac{I_{S2}}{I_{S1}}$

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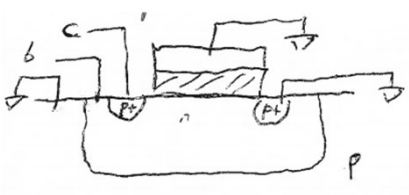
# Band Gap Details

- V_OUT = 1.26V, about the band gap of silicon in eV (but unrelated)
- Temperature variation: parabolic, concave down, a few mV over 100C
- Implement in CMOS w/ parasitic susbstrate PNP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