Voltage references

I. Passive reference

II. Resistor-MOS reference

III. Bipolar reference

IV. MOS reference

Important parameters:

- Power supply Sensitivity:
  \[ S_{V_{ref}}^{V_{DD}} = \frac{V_{DD}}{V_{ref}} \frac{\partial V_{ref}}{\partial V_{DD}} \]
  \[ \frac{\Delta V_{ref}}{V_{ref}} = S_{V_{DD}}^{V_{ref}} \left( \frac{\Delta V_{DD}}{V_{DD}} \right) \]

- Temperature coefficient:
  \[ TC = \frac{1}{V_{ref}} \frac{\partial V_{ref}}{\partial T} = \frac{1}{T} S_{T}^{V_{ref}} \left( \frac{ppm}{^\circ C} \right) \]
I. Passive reference

\[ V_{\text{ref}} = V_{DD} \frac{R_2}{R_1 + R_2} \]
\[ S_{V_{\text{DD}}}^{V_{\text{ref}}} = \frac{V_{DD}}{V_{\text{ref}}} \frac{\partial V_{\text{ref}}}{\partial V_{DD}} = 1 \]
\[ TC = \frac{1}{V_{\text{ref}}} \frac{\partial V_{\text{ref}}}{\partial T} = \frac{R_1}{R_1 + R_2} \left( TC(R_2) - TC(R_1) \right) \]

(supposed \( \frac{\partial V_{DD}}{\partial T} = 0 \))

If \( TC(R_1) = TC(R_2) \rightarrow TC = 0 \), same type of resistors.

II. MOS reference

\[ V_{\text{ref}} = V_{GS} = V_{TH} + \sqrt{\frac{V_{DD}}{\beta R_1}} \] (supposed \( V_{DD} \gg V_{\text{ref}} \))
\[ S_{V_{\text{DD}}}^{V_{\text{ref}}} \approx \frac{V_{DD}}{2 V_{\text{ref}} \sqrt{\beta R_1 (V_{DD} - V_{\text{ref}})}} \]
\[ \frac{\partial V_{\text{ref}}}{\partial T} = \frac{\partial V_{T0}}{\partial T} - \frac{1}{2} \sqrt{\frac{2n V_{DD}}{\beta R_1}} \left( \frac{1}{R_1} \frac{\partial R_1}{\partial T} + \frac{1}{\beta} \frac{\partial \beta}{\partial T} \right) \]
\[ TC = \frac{V_{T0}}{V_{\text{ref}}} TC(V_{T0}) - \frac{1}{2 V_{\text{ref}}} \sqrt{\frac{2n V_{DD}}{\beta R_1}} \left( TC(R_1) - TC(\beta) \right) \]
III. Bipolar reference

\[ V_{ref} \approx V_T \ln \left( \frac{V_{DD} - V_{ref}}{R_1 I_S} \right) \]

\[ V_{ref} \approx V_T \ln \left( \frac{V_{DD}}{R_1 I_S} \right) \] (supposed \( V_{DD} >> V_{ref} \))

\[ S_{V_{DD}}^{V_{ref}} = \frac{1}{\ln \left( \frac{V_{DD}}{R_1 I_S} \right)} \]

\[ \frac{\partial V_{ref}}{\partial T} = \frac{V_{ref}}{T} - V_T \left( \frac{1}{I_s} \frac{\partial I_s}{\partial T} + \frac{1}{R_1} \frac{\partial R_1}{\partial T} \right) \]

\[ TC = \frac{V_{ref}}{T} - V_T (TC(I_s) - TC(R_1)) \]

Numbers start to get difficult to compare;

Normally:

\[ S_{V_{DD}}^{V_{ref}} \big|_{MOS} > S_{V_{DD}}^{V_{ref}} \big|_{BJT} \]

\[ TC \big|_{MOS} < TC \big|_{BJT} \]

Usually sensitivity studies are performed by means of simulation.
IV. MOS reference

Assuming same current flow to both transistors;

\[ V_{ref} = V_{THN} + \frac{V_{DD} - V_{THN} - |V_{THP}|}{\sqrt{\frac{\beta_1}{\beta_2}} + 1} \]

\[ S_{V_{DD}} = \frac{V_{DD}}{V_{DD} - V_{THN} + \sqrt{\frac{\beta_1}{\beta_2}} - |V_{THP}|} \approx 1 \]

\[ TC = \frac{1}{V_{ref}} \frac{1}{\sqrt{\frac{\beta_1}{\beta_2}} + 1} \left[ \frac{\partial(-V_{THP})}{\partial T} + \frac{\beta_1}{\beta_2} \frac{\partial V_{THN}}{\partial T} \right] \]
Try to avoid $V_{DD}$ dependent output.

$M_3$ and $M_4$ mirrors make $I_1 = I_2$;

$$IR = V_{GSM_1} = V_{THN} + \sqrt{\frac{2I}{\beta_1}}$$

$$I_{ref} \approx \frac{V_{THN}}{R}$$ for large $\beta$

**Caution!!**

Two operating points:

A  No current:
   $V_{GM3,4} = V_{DD}$
   $V_{G2} = 0$

B  $I_{ref}$

**Startup circuit needed!!**
**Startup needed to set operation point**

When $V_{GM2}$ goes low $M_6$ starts to increase current driving operation point to the desired current.
Self biased BJT

\[ I = \frac{V_{D1}}{R} = I_S e^{\frac{V_{D1}}{nV_T}} \]

Better matching due to cascode mirrors.

Caution!!

Startup circuit also needed!!
Current references

- Mirrors formed by $M_1$ to $M_8$ force same current;
  \[ V_{D_1} = V_{D_2} + I_{D_2}R \]
- Emitter of $D_2$ is $K$ times $D_1$;
  \[ I = \frac{nkln(K)}{qR} = \frac{nV_T}{R} \ln(K) \]
All previous circuits suffer from temperature dependence.

Some of previous have **positive** TC while others **negative** TC.

Combine both TCs to achieve a common TC = 0.

BJT $\Delta V_{BE}$ variation with temperature;

$$\frac{\partial (\Delta V_{BE})}{\partial T} = \alpha \frac{\partial V_T}{\partial T} = \alpha \frac{\partial}{\partial T} \left( \frac{kT}{q} \right) = \alpha \frac{k}{q} = \alpha 0.085 \frac{mV}{\circ C}$$

Proportional to absolute temperature (PTAT)
Cancel temperature dependence:
\[
\frac{\partial V_{out}}{\partial T} = \frac{\partial V_{BE}}{\partial T} + \alpha \frac{\partial V_T}{\partial T}
\]
\[
\frac{\partial V_{BE}}{\partial T} = -\alpha \frac{\partial V_T}{\partial T}
\]
\[
\alpha = \frac{2\,mV/°C}{0.085\,mV/°C} \approx 23.53
\]
For \( V_T = 26\,mV @ 25° C \) output is around 1.2V, close to the \textbf{silicon band gap voltage}. 
Song Bandgap reference

- Currents copied by mirrors; 
  \[ V_{BE1} = V_{BE2} + I_{D2}R \]
- PTAT current; 
  \[ I_{PTAT} = I_2 = \frac{V_{BE1} - V_{BE2}}{R} = \frac{V_T}{R} \ln \left( \frac{l_1}{l_2} \frac{l_5}{l_1} \right) \]
- If \( D_2 \) is \( N \) times larger than \( D_1 \); 
  \[ I_{PTAT} = \frac{V_T}{R} \ln N \]
- Output voltage; 
  \[ V_{ref} = V_{BE3} + V_T \frac{R_2}{R_1} \ln N = V_{BE3} + \alpha V_T \]
- If \( R_2 = LR_1 \); 
  \[ V_{ref} = V_{BE3} + V_T L \ln N = V_{BE3} + \alpha V_T \]
Brokaw Bandgap reference

Currents copied by mirrors;
\[ V_{BE1} = V_{BE2} + I_{D2} R \]

PTAT current;
\[ I_1 = I_2 = \frac{V_{BE1} - V_{BE2}}{R_2} = \frac{V_T}{R_2} \ln \left( \frac{l_1}{l_2} \frac{l_{S2}}{l_{S1}} \right) = \frac{V_T}{R} \ln N \]

Output voltage;
\[ V_{ref} = V_{BE1} + R_1(I_1 + I_2) = V_{BE1} + V_T \frac{2R_1}{R_2} \ln N = V_{BE1} + \alpha V_T \]
CMOS technologies usually have only lateral PNP bipolar transistors available. Usually called sub-bandgap due to lower output voltage.

\[
V_{EB1} = V_{EB2} + I_2 R_1 \\
I_2 = \frac{V_{EB1} - V_{EB2}}{R_1} = \\
\frac{V_T}{R_1} \ln \left( \frac{l_1 l_2 l_5}{l_1 l_2 l_1} \right) = \frac{V_T}{R_1} \ln N \\
I_3 = I_2 - I_4 - I_5 = \\
I_2 - \frac{V_{ref}}{R_4 + R_5} - \frac{V_{ref} R_5}{R_3 (R_4 + R_5)} \\
V_{ref} = V_{EB3} + I_3 R_2 \\
V_{ref} = \beta \left( V_{EB3} + \alpha V_T \right)
\]

With \( \beta \) independent with temperature and smaller than 1.
Exercise 1: Elements dependence on temperature

On Ex8 library you can find a cellview named Bipolar where you can see a linear effect on temperature. On the RdivRef check the performance with temperature variation and with power supply variation;

- What is the TC?
- What is the Sensitivity to power supply?
Exercise 2: Bandgap references

With the Song and Brokaw schematics try to tune the parameters to get an acceptable voltage output dependent on temperature;

- What is the TC?
- What is the Sensitivity to power supply?
Exercise 3: CMOS Bandgap reference

Design a sub-bandgap CMOS reference using ideal amplifier \textit{vcvs} from analogLib.

- What is the TC?
- What is the Sensitivity to power supply?