Clocked Comparator

Preamplifier with offset compensation and regenerative latch

Gain of preamplifier may still not be large enough
ADC Types

Nyquist Rate
- Flash
- Pipeline
- Two-Step Flash
- Multi-Step Flash
- Cyclic (algorithmic)
  - Successive Approximation
  - Folded
  - Dual Slope

Over-Sampled
- Single-bit
- Multi-bit
- First-order
- Higher-order
- Continuous-time

All have comparable conversion rates
Basic approach in all is very similar

Review from last lecture
Pipelined ADC Stage $k$

Pipeline Stage

$X_{INk}$ $\rightarrow$ ADC$_k$ $\rightarrow$ DAC$_k$ $\rightarrow$ $+$ $\rightarrow$ $A_k$ $\rightarrow$ $S/H_k$ $\rightarrow$ $X_{OUTk}$

$V_{REF}$ $\rightarrow$ $d_k$ $\rightarrow$ $n_k$ $\rightarrow$ $C_{LK}$

Review from last lecture.
Pipelined ADC Stage $k$

Pipeline Stage

$X_{INk}$ $+$ $A_k$ $S/H_k$ $X_{OUTk}$

$ADC_k$ $DAC_k$

$n_k$ $d_k$ $V_{REF}$

$C_{LK}$

Usually Realized as Single SC Block
1-bit/Stage Pipeline Implementation

Review from last lecture.

\[ V_O = \begin{cases} 
2V_{IN} + \frac{V_{REF}}{2} & \text{if } V_{IN} < 0 \\
2V_{IN} - \frac{V_{REF}}{2} & \text{if } V_{IN} > 0 
\end{cases} \]
Voltage Reference

- Review from last lecture.

Voltage Reference Circuit

- $V_{\text{BIAS}}$ to $V_{\text{REF}}$
Current Reference

\[ V_{BIAS} \rightarrow \text{Current Reference Circuit} \rightarrow I_{REF} \]

\[ I_{REF} \]
Desired Properties of References

- Accurate
- Temperature Stable
- Time Stable
- Insensitive to $V_{\text{BIAS}}$
- Low Output Impedance (voltage reference)
- Floating
- Small Area
- Low Power Dissipation
- Process Tolerant
- Process Transportable
Consider Voltage References

\[ V_{DD}, V_T \text{ reference} \]

\[ V_{REF} = \frac{V_{DD} - V_{T0} \left( 1 - \sqrt[2]{\frac{W_2 L_1}{W_1 L_2}} \right)}{1 + \sqrt[2]{\frac{W_2 L_1}{W_1 L_2}}} \]

Observation – Variables with units Volts needed to build any voltage reference
Voltage References

Observation – Variables with units Volts needed to build any voltage reference

What variables available in a process have units volts?

\[ V_{DD}, \ V_T, \ V_{BE} \ (\text{diode}) , \ V_Z, V_{BE}, V_t \ ??? \]

What variables which have units volts satisfy the desired properties of a voltage reference?

How can a circuit be designed that “expresses” the desired variables?
Voltage References

Consider the Diode

\[ I_D = J_S A e^{\frac{V_D}{V_t}} \]

\[ J_S = \tilde{J}_{SX} \left[ T^m e^{\frac{-V_{G0}}{V_t}} \right] \]

\[ \frac{kT}{q} = \frac{1.38 \times 10^{-23}}{1.602 \times 10^{-19}} \frac{V}{^0K} = 8.614 \times 10^{-5} \frac{V}{^0K} \]

\[ V_{G0} = 1.206V \]

termed the bandgap voltage

pn junction characteristics highly temperature dependent through both the exponent and \( J_S \)

\( V_{G0} \) is nearly independent of process and temperature
Voltage References

Observation – Variables with units Volts needed to build any voltage reference

What variables available in a process have units volts?

$V_{DD}, V_T, V_{BE}$ (diode), $V_Z, V_{BE}, V_t, V_{G0}$

What variables which have units volts satisfy the desired properties of a voltage reference? $V_{G0}$ and ??

How can a circuit be designed that “expresses” the desired variables?

$V_{G0}$ is deeply embedded in a device model with horrible temperature effects!
Good diodes are not widely available in most MOS processes!
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These diodes interact and actually form substrate pnp transistor.

Not practical to forward bias junction.
Good diodes are not widely available in most MOS processes!
Voltage References

Bandgap Voltage Appears in BJT Model Equation as well
Voltage references that “express” the bandgap voltage are termed “Bandgap References”.

$V_{G0}$ is deeply embedded in a device model with horrible temperature effects!

Good BJTs are not widely available in most MOS processes but the substrate pnp is available!
Standard Approach to Building Voltage References

Negative Temperature Coefficient (NTC)

Positive Temperature Coefficient (PTC)

\[ X_{\text{OUT}} = X_N + KX_P \]

Pick K so that at some temperature \( T_0 \),

\[ \frac{\partial(X_N + KX_P)}{\partial T} \bigg|_{T=T_0} = 0 \]
Standard Approach to Building Voltage References

\[ V \]

Negative Temperature Coefficient

Positive Temperature Coefficient

\[ T_0 \]
Standard Approach to Building Voltage References

$$V = X_N + KX_P$$

$$\frac{\partial (X_N + KX_P)}{\partial T} \bigg|_{T=T_0}$$
Bandgap Voltage References

Consider two BJTs (or diodes)

\[
I_C(T) = \left( \tilde{I}_{SX} \left[ T^m e^{-\frac{V_G}{V_t}} \right] \right) e^{\frac{V_{BE}(T)}{V_t}}
\]

\[
V_{BE} = V_t \ln(I_C) + \left[ V_{G0} - V_t \left( \ln(\tilde{I}_{SX} A_e) + m \ln(T) \right) \right]
\]

\[
V_{BE2} - V_{BE1} = \Delta V_{BE} = \left[ \frac{k}{q} \ln \left( \frac{I_{C2}}{I_{C1}} \right) \right] T
\]

If the $I_{C2}/I_{C1}$ ratio is constant, the TC of $\Delta V_{BE}$ is positive

$\Delta V_{BE}$ is termed a PTAT voltage (Proportional to Absolute Temperature)

This relationship applies irrespective of how temperature dependent $I_{C1}$ and $I_{C2}$ may be provided the ratio is constant!!
Bandgap Voltage References

Consider two BJTs (or diodes)

\[ V_{BE2} - V_{BE1} = \Delta V_{BE} = \left[ \frac{k \ln \left( \frac{I_{C2}}{I_{C1}} \right)}{q} \right] T \]

\[ \frac{\partial (V_{BE2} - V_{BE1})}{\partial T} = \frac{k}{q} \ln \left( \frac{I_{C2}}{I_{C1}} \right) \]

At room temperature

\[ V_{BE2} - V_{BE1} = [8.6 \times 10^{-5} \times 300] = 25.8 \text{mV} \]

If \( \ln(I_{C2}/I_{C1}) = 1 \)

\[ \left. \frac{\partial (V_{BE2} - V_{BE1})}{\partial T} \right|_{T=T_0=300^\circ K} = 8.6 \times 10^{-5} = 86 \mu V/^\circ C \]

The temperature coefficient of the PTAT voltage is rather small
Bandgap Voltage References

Consider two BJTs (or diodes)

\[ \frac{\partial (V_{BE2} - V_{BE1})}{\partial T} = \frac{k}{q} \ln \left( \frac{I_{C2}}{I_{C1}} \right) \]

At room temperature

The temperature coefficient of the PTAT voltage is rather small even if large collector current ratios are used
Bandgap Voltage References

Consider two BJTs (or diodes)

\[
I_C(T) = \left( I_{SX} \left[ T^m e^{\frac{-V_G}{V_t}} \right] \right) e^{\frac{V_{BE}(T)}{V_t}}
\]

\[
V_{BE} = V_t \ln(I_C) + [V_{G0} - V_t \left( \ln(J_{SX}A_E) + m \ln(T) \right)]
\]

If \( I_C \) is independent of temperature, it follows that

\[
\frac{\partial V_{BE}}{\partial T} = \frac{k}{q} \left[ -m + \left( \frac{V_{BE} - V_{G0}}{V_t} \right) \right]
\]

\[
\frac{\partial V_{BE}}{\partial T} \bigg|_{T=T_0=300^\circ K} \approx 8.6 \times 10^{-5} \left[ -2.3 + \left( \frac{0.65 - 1.2}{25 \text{mV}} \right) \right] \approx -2.1 \text{mV/}^\circ \text{C}
\]
Bandgap Voltage References

Consider two BJTs (or diodes)

If $I_C$ is independent of temperature, it follows that

$$\frac{\partial V_{BE}}{\partial T} \bigg|_{T=T_0=300^\circ K} \approx 8.6 \times 10^{-5} \left[ -2.3 + \left( \frac{0.65 - 1.2}{25 \text{mV}} \right) \right] \approx -2.1 \text{mV/}^\circ \text{C}$$

If $\ln(I_{C2}/I_{C1})=1$

$$\frac{\partial (V_{BE2} - V_{BE1})}{\partial T} \bigg|_{T=T_0=300^\circ K} = 8.6 \times 10^{-5} = 86 \mu \text{V/}^\circ \text{C}$$

Magnitude of TC of PTAT source is much smaller than that of $V_{BE}$ source

If 

$$\frac{\partial (X_N + KX_P)}{\partial T} \bigg|_{T=T_0} = 0$$

$K$ will be large

$$X_{\text{OUT}} = X_N + KX_P$$
Standard Approach to Building Voltage References

![Diagram showing temperature and voltage relationship with negative and positive temperature coefficients]
Standard Approach to Building Voltage References

\[ \frac{\partial (X_N + KX_P)}{\partial T} \bigg|_{T=T_0} \]

\[ X_N + KX_P \]

\[ T_0 \]

\[ T \]

\[ V \]

\[ V \]

Negative Temperature Coefficient

Positive Temperature Coefficient
Bandgap Voltage References

Consider two BJTs (or diodes)

\[
I_C(T) = I_{SX} \left[ T^m e^{-\frac{V_G}{V_t}} \right] e^{\frac{V_{BE}(T)}{V_t}}
\]

\[
V_{BE} = V_t \ln(1) + \left[ V_G - V_t \left( \ln(J_{SX} A_E) + m \ln(T) \right) \right]
\]

\[
V_{BE2} - V_{BE1} = \Delta V_{BE} = \left[ \frac{k}{q} \ln\left( \frac{I_{C2}}{I_{C1}} \right) \right] T
\]

If the \( I_{C2}/I_{C1} \) ratio is constant, the TC of \( \Delta V_{BE} \) is positive

\( \Delta V_{BE} \) is termed a **PTAT voltage** (Proportional to Absolute Temperature)

This relationship applies irrespective of how temperature dependent \( I_{C1} \) and \( I_{C2} \) may be provided the ratio is constant !!
Bandgap Voltage References

Consider two BJTs (or diodes)

\[
\begin{align*}
V_{BE2} - V_{BE1} &= \Delta V_{BE} = \left[\frac{k}{q} \ln \left(\frac{I_{C2}}{I_{C1}}\right)\right]T \\
\frac{\partial (V_{BE2} - V_{BE1})}{\partial T} &= \frac{k}{q} \ln \left(\frac{I_{C2}}{I_{C1}}\right)
\end{align*}
\]

At room temperature

\[
V_{BE2} - V_{BE1} = \left[8.6 \times 10^{-5} \times 300\right] = 25.8 \text{mV}
\]

If \(\ln(I_{C2}/I_{C1}) = 1\)

\[
\left.\frac{\partial (V_{BE2} - V_{BE1})}{\partial T}\right|_{T=T_0=300^\circ K} = 8.6 \times 10^{-5} = 86 \mu V/^\circ C
\]

The temperature coefficient of the PTAT voltage is rather small
Bandgap Voltage References

Consider two BJTs (or diodes)

\[
\frac{\partial (V_{BE2} - V_{BE1})}{\partial T} = \frac{k}{q} \ln \left( \frac{I_{C2}}{I_{C1}} \right)
\]

At room temperature

The temperature coefficient of the PTAT voltage is rather small even if large collector current ratios are used
Bandgap Voltage References

Consider two BJTs (or diodes)

\[
I_C(T) = \left( I_{SX} \left[ T^m e^{-\frac{V_{G0}}{V_t}} \right] e^{\frac{V_{BE}(T)}{V_t}} \right)
\]

\[
V_{BE} = V_t \ln(I_C) + \left[ V_{G0} - V_t \ln\left( \frac{J_{sx} A_e}{m} \right) \right]
\]

If \( I_C \) is independent of temperature, it follows that

\[
\frac{\partial V_{BE}}{\partial T} = \frac{k}{q} \left[ -m + \left( \frac{V_{BE} - V_{G0}}{V_t} \right) \right]
\]

\[
\left. \frac{\partial V_{BE}}{\partial T} \right|_{T = T_0 = 300^\circ K} \approx 8.6 \times 10^{-5} \left[ -2.3 + \left( \frac{0.65 - 1.2}{25 \text{mV}} \right) \right] \approx -2.1 \text{mV/}^\circ \text{C}
\]
Bandgap Voltage References

Consider two BJTs (or diodes)

\[
\begin{align*}
\frac{\partial V_{BE}}{\partial T} \bigg|_{T=T_0=300^\circ K} & \approx 8.6 \times 10^{-5} \left[-2.3 + \left( \frac{0.65 - 1.2}{25 \text{mV}} \right) \right] \approx -2.1 \text{mV/}^\circ \text{C} \\
\text{If } \ln(I_{C2}/I_{C1})=1 \\
\frac{\partial (V_{BE2} - V_{BE1})}{\partial T} \bigg|_{T=T_0=300^\circ K} & = 8.6 \times 10^{-5} = 86 \mu \text{V/}^\circ \text{C}
\end{align*}
\]

Magnitude of TC of PTAT source is much smaller than that of \( V_{BE} \) source.

If \( \frac{\partial (X_N + KX_P)}{\partial T} \bigg|_{T=T_0} = 0 \), K will be large

\[ X_{OUT} = X_N + KX_P \]
Bandgap Voltage References

Consider two BJTs (or diodes)

\[
V_{BE} = V_t \ln(I_C) + \left[ V_{G0} - V_t \left( \ln(J_{Sx}A_E) + m \ln T \right) \right]
\]

If \( I_C \) is independent of temperature, it follows that

\[
\frac{\partial V_{BE}}{\partial T} \bigg|_{T=T_0=300^\circ K} \approx 8.6 \times 10^{-5} \left[ -2.3 + \left( \frac{0.65 - 1.2}{25 \text{mV}} \right) \right] \approx -2.1 \text{mV/}^\circ \text{C}
\]

Rewriting \( V_{BE} \) equation

\[
V_{BE} = V_{G0} + \left( V_t \ln(I_C) + \left[ m \ln T - V_t \left( \ln(J_{Sx}A_E) \right) \right] \right)
\]

If \( I_C \) is reasonably independent of temperature, \( V_{BE} \) will still provide a negative TC
Response to question from last time:

\[ V_G = V_{G0} - \frac{\alpha T^2}{T + \beta} \]

\[ V_{G0} = 1.16V, \alpha = 0.000702^{\circ}K^{-1} \text{ and } \beta = 1108^{\circ}K. \]

Total contribution of temperature dependent term at 300K is about 2.1mV.

Not good agreement in industry about exact values of \( \alpha \) and \( \beta \) or even exact functional form.

Does introduce a small error but not real big.

This is the model for \( V_G \) that is included in SPICE.
Bandgap Reference Circuits

- Circuits that implement $\Delta V_{BE}$ and $V_{BE}$ or $\Delta V_D$ and $V_D$ widely used to build bandgap references.
$V_{BE}$ and $\Delta V_{BE}$ with constant $I_C$
$V_{BE}$ plot for constant $I_C$

![Graph showing $V_{BE}$ against temperature with end point and fit line indicated.](image-url)
Comparison of $V_{BE}$ with constant current and PTAT current
First Bandgap Reference (and still widely used!)

End of Lecture 40