UiO : Department of Informatics
University of Oslo

INF4420

Reference circuits

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Outline

Reference circuits and bias circuits

Uses of reference circuits and bias cicuits

MOSFET based references

Parasitic diode based references (bandgaps)

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Reference circuits

"Bandgaps". Why?

Every analog and mixed-signal system needs a stable reference.

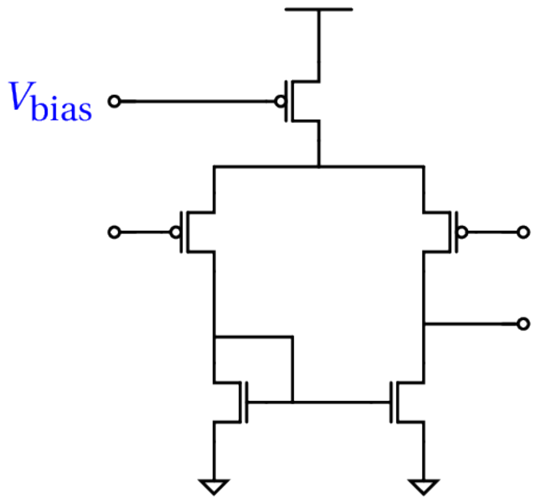
The reference circuit presents some physical quantity (voltage, current, frequency, other?)

Image courtesy of Texas Instruments

Biasing an analog circuit

Analog circuits need a current source to set the operating point.

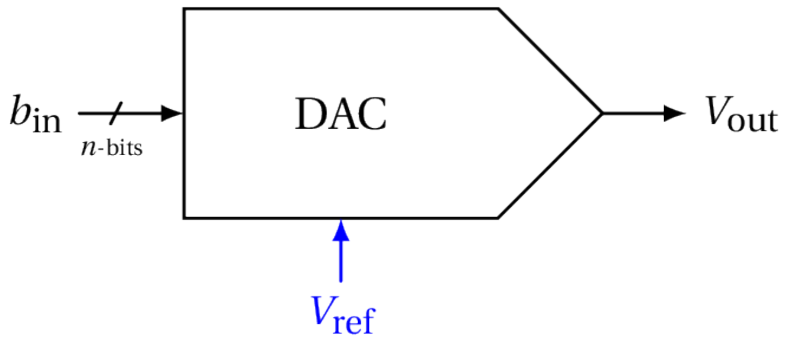
Circuit performance very dependent on the biasing.



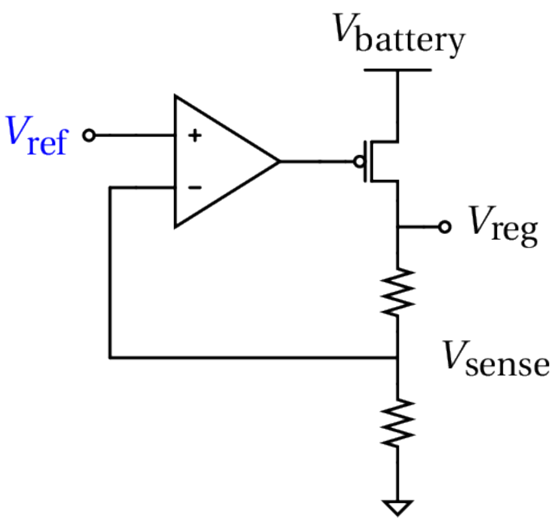
Data converters

Binary word input is dimensionless.

Need to multiply the dimensionless input with a dimensioned (physical) reference.



Voltage supply regulation



Temperature behaviour

Predictable behaviour across temperature

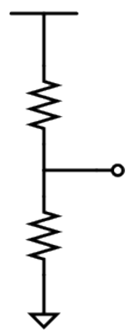
- Constant
- Proportional (PTAT)

Additionally, insensitive to supply voltage and process variations (PVT).

A very simple reference

Careful layout gives good matching between resistors

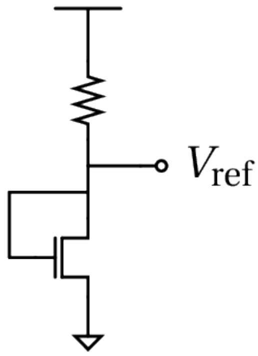
- Temperature affects resistors equally, good TC
- Precisely defined Vref as ratio of Vdd
- Precise value of Vdd is not known (bad)
- Poor PSRR! (bad)



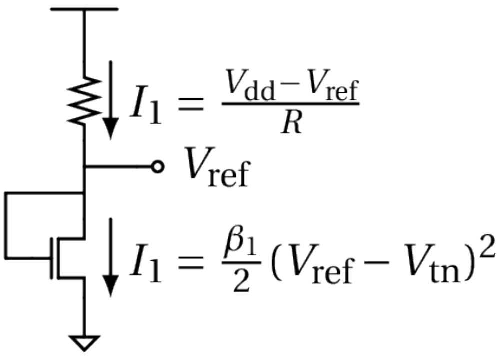
MOSFET-R reference

Can be used to generate a bias voltage or reference voltage.

Better PSRR than the voltage divider.



MOSFET-R reference

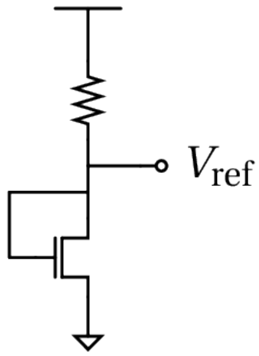


MOSFET-R reference

$$\Rightarrow V_{\text{ref}} = V_{\text{tn}} + \sqrt{\frac{2I_1}{\beta_1}}$$

$$= V_{\text{tn}} + \sqrt{\frac{2(V_{\text{dd}} - V_{\text{ref}})}{R\beta_1}}$$

$$\Rightarrow V_{\text{ref}} = V_{\text{tn}} + \frac{\sqrt{1 + 2R\beta_1(V_{\text{dd}} - V_{\text{tn}})} - 1}{R\beta_1}$$

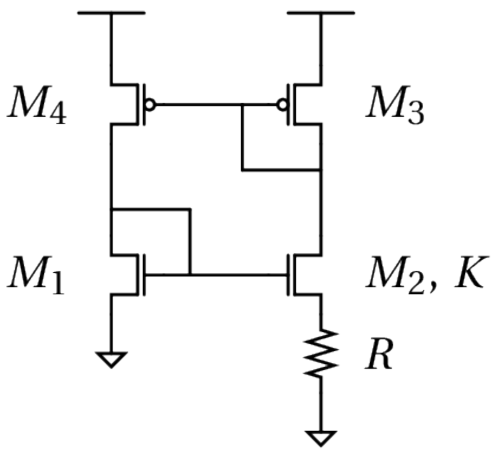


Beta multiplier reference

Deriving Iref from Iout

Less dependence on Vdd

Can be used for biasing and reference



Beta multiplier reference

$$V_{GS1} = V_{GS2} + I_{REF} R$$

$$\sqrt{\frac{2 I_{REF}}{\beta_1}} + V_{TN} = \sqrt{\frac{2 I_{REF}}{\beta_2}} + V_{TN} + I_{REF} R$$

$$I_{REF} = \frac{2}{\beta_1} \frac{1}{R^2} \left(1 - \frac{1}{\sqrt{K}}\right)^2$$

Beta multiplier reference

$$I_{REF} = I_{D1} = \frac{2}{\beta_1} \frac{1}{R^2} \left(1 - \frac{1}{\sqrt{K}}\right)^2$$

$$g_{m1} = \sqrt{2\beta_1 I_{D1}} = \frac{2}{R} \left(1 - \frac{1}{\sqrt{K}}\right)$$

$$K = 4 \Rightarrow g_{m1} = \frac{1}{R}$$

Beta multiplier reference

As a voltage reference, take Vgs1 to be the reference voltage, Vref.

We know the current, Iref. Use this to find Vgs1=Vref

We must find the sensitivity of Vref to Vdd and T

Beta multiplier reference

$$I_{\mathrm{REF}} = I_{\mathrm{D1}} = \frac{2}{\beta_1}\frac{1}{R^2}\left(1 - \frac{1}{\sqrt{K}}\right)^2$$

$$V_{\mathrm{REF}} = V_{\mathrm{GS1}} = \sqrt{\frac{2I_{\mathrm{D1}}}{\beta_1}} + V_{\mathrm{TN}}$$

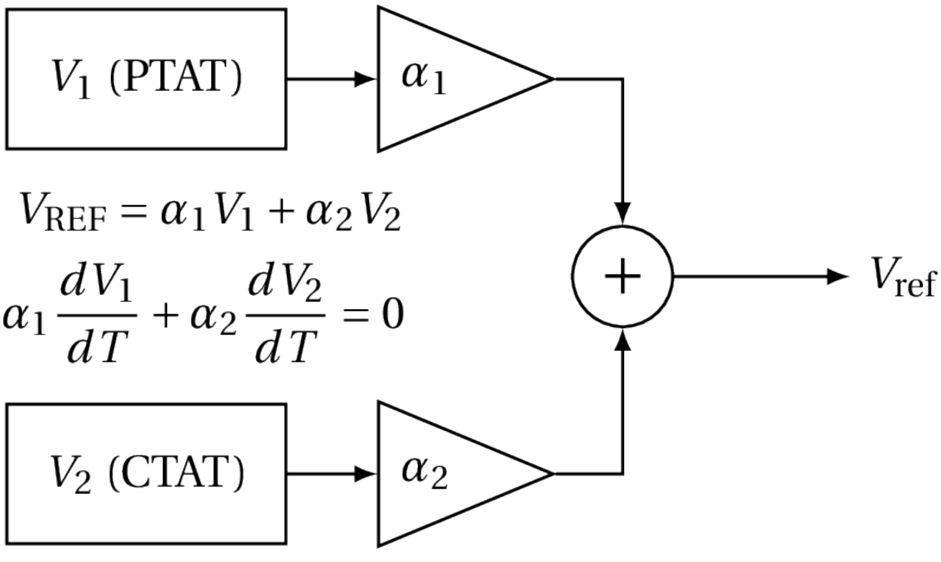
$$\Rightarrow V_{\mathrm{REF}} = \frac{2}{R\beta_1}\left(1 - \frac{1}{\sqrt{K}}\right) + V_{\mathrm{TN}}$$

$$= \frac{1}{R\beta_1} + V_{\mathrm{TN}}, \text{ with } K = 4$$

Bandgaps

It turns out, we can make references with less temperature dependence using bipolar transistors.

Temperature independence



$$V_{REF} = \alpha_1 V_1 + \alpha_2 V_2$$

$$\alpha_1 \frac{dV_1}{dT} + \alpha_2 \frac{dV_2}{dT} = 0$$

Parasitic diode CTAT and PTAT

Need elements with well defined temperature behaviour. We will use diode connected BJTs.

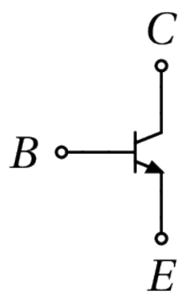
CTAT from Vbe (biased with constant current)

PTAT from "delta Vbe" (biased with ratioed current or emitter area), result is the thermal voltage, Vt

Bipolar transistor diodes

Current sinked by the device is affected by temperature

- Vt is the thermal voltage (proportional to T), 26 mV @ RT
- Is is also a function of termperature

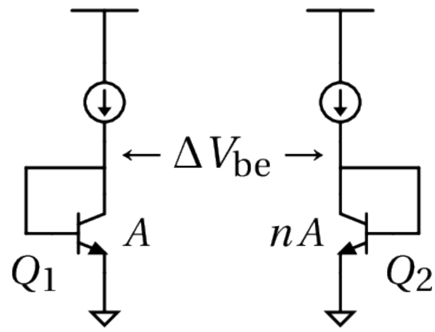


$$I_C = I_S e^{\frac{V_{BE}}{V_T}}$$

$$V_T = \frac{kT}{q}$$

PTAT voltage

$$V_{\text{BE}} = V_T \ln \frac{I_C}{I_S}$$



$$\begin{aligned}\Delta V_{\text{BE}} &= V_{\text{BE1}} - V_{\text{BE2}} \\ &= V_T \ln \frac{I_1}{I_S} - V_T \ln \frac{I_1}{nI_S} \\ &= V_T (\ln I_1 - \ln I_S - \ln I_1 + (\ln n + \ln I_S)) \\ &= V_T \ln n\end{aligned}$$

PTAT voltage

To find temperature behaviour, we take the derivative wrt. temperature (assume the first derivative is constant)

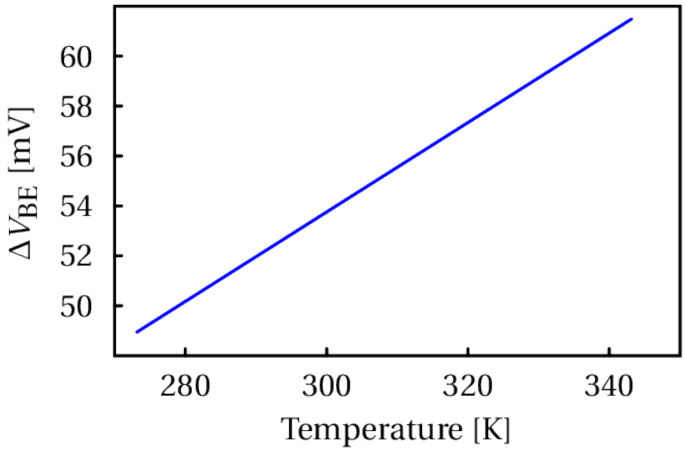
Delta Vbe is proportional to absolute temperature. Defined by two physical constants and emitter ratio, n.

$$\Delta V_{\text{BE}} = V_T \ln n$$

$$V_T = \frac{kT}{q}$$

$$\frac{d\Delta V_{\text{BE}}}{dT} = \frac{k}{q} \ln n = 86.2 \ln n \ \frac{\mu\text{V}}{\text{K}}$$

PTAT voltage



CTAT voltage

For the full bandgap circuit, we need both PTAT and CTAT.

Is exhibits temperature dependence. In the delta Vbe, Is is canceled. By looking at a single junction Vbe, we get a contribution from Is. dVbe/dT assuming constant current Ic.

In this case, the overall TC is CTAT.

CTAT voltage

$$V_{\text{BE}} = V_T \ln \frac{I_C}{I_S}$$

$$\frac{dV_{\text{BE}}}{dT} = \frac{V_{\text{BE}} - (4+m)V_T - \frac{E_g}{q}}{T}$$

$$(uv)' = u'v' + uv'$$

$$\left(\frac{u}{v}\right)' = \frac{u'v - uv'}{v^2}$$

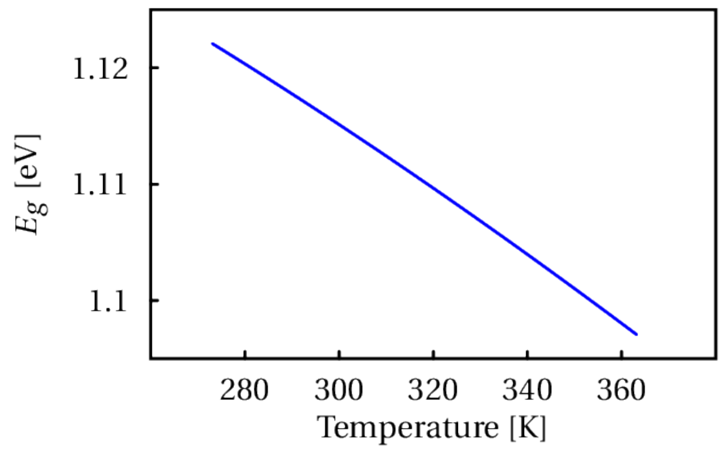
$$(\ln h(x))' = \frac{h'(x)}{h(x)}$$

$$\left(x^n\right) = nx^{n-1}$$

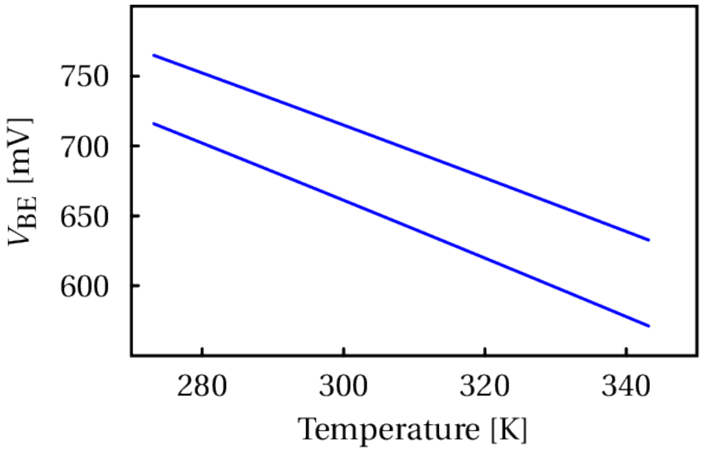
$$e^u = e^u u'$$

CTAT voltage

Silicon bandgap energy as a function of temperature



CTAT voltage

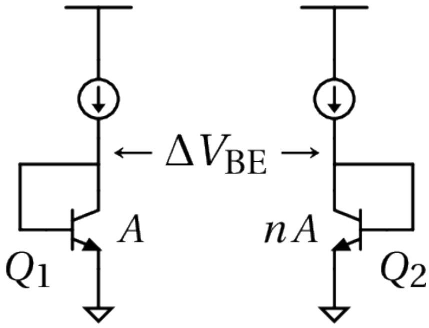


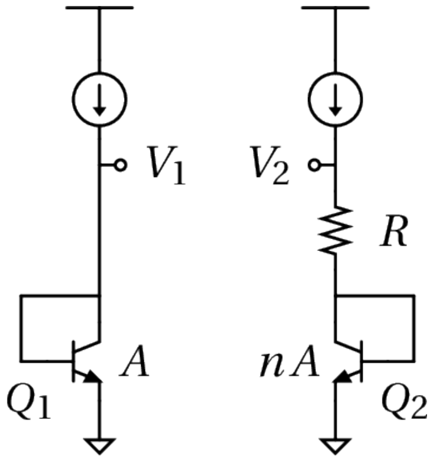
Bandgap circuits

We know how to generate PTAT and CTAT, and how we should combine these contributions for temperature independence (I. e. scale and add to acheive temperature independence).

How do we make a circuit that realizes this system?

Bandgap circuits





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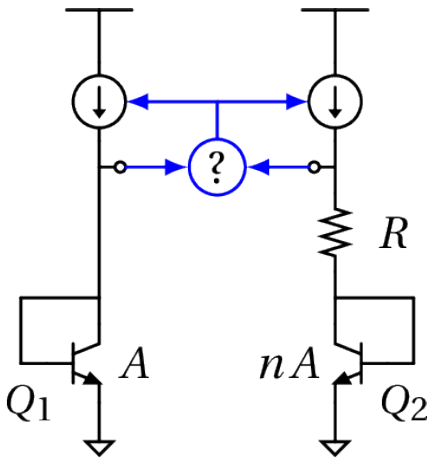
Bandgap circuits

Need a circuit that can sense V1 and V2 and adjust the current sources so that V1=V2

V2 = Vbe2 + Vt ln n

ln n must be 17.2 for V2 to be independent of T



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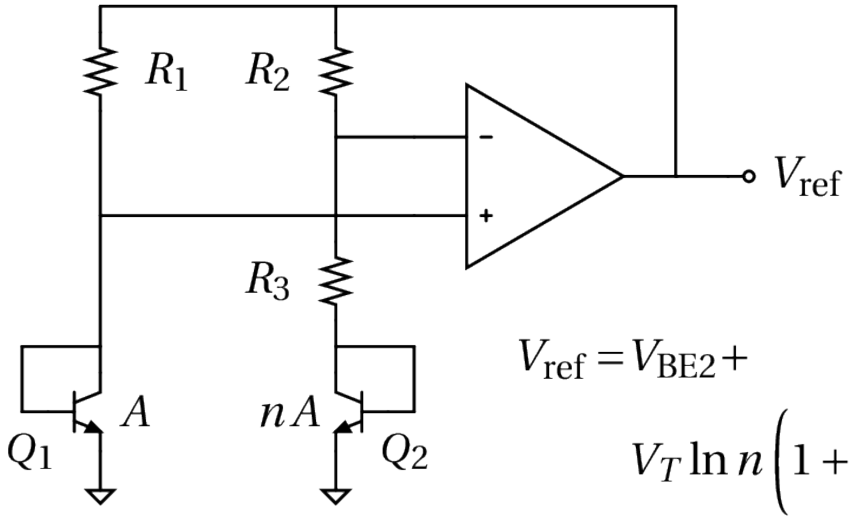
Bandgap circuits



$$V_{\text{ref}} = V_{\text{BE2}} + V_T \ln n \left(1 + \frac{R_2}{R_3}\right)$$

Bandgap circuits

$$V_{\text{ref}} = V_{\text{BE2}} + V_T \ln n \left(1 + \frac{R_2}{R_3}\right)$$

$$V_{\text{ref}} = \alpha_1 V_1 + \alpha_2 V_2$$

$$\text{Zero TC} \Rightarrow \alpha_1 \frac{dV_1}{dT} + \alpha_2 \frac{dV_2}{dT} = 0$$

$$\alpha_1 \frac{dV_{\text{BE2}}}{dT} + \alpha_2 \frac{dV_T}{dT} = 0$$

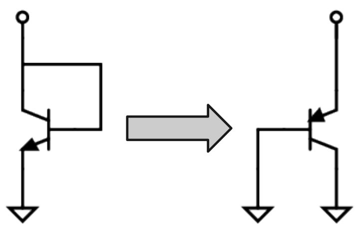
$$\Rightarrow \alpha_1 = 1,\ \alpha_2 = -\frac{dV_{\text{BE2}}}{dT} \frac{T}{V_T},\ \alpha_2 = \ln n \left(1 + \frac{R_2}{R_3}\right)$$

Bandgap circuits

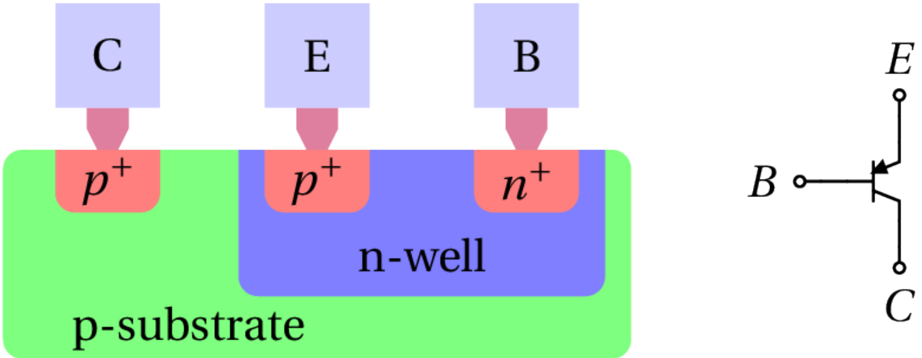
This circuit is used for illustration purposes. Working with CMOS, there are a number of issues with this circuit which we will discuss in the following slides. We will try to find circuits which are more practical and CMOS compatible.

A more CMOS friendly BJT

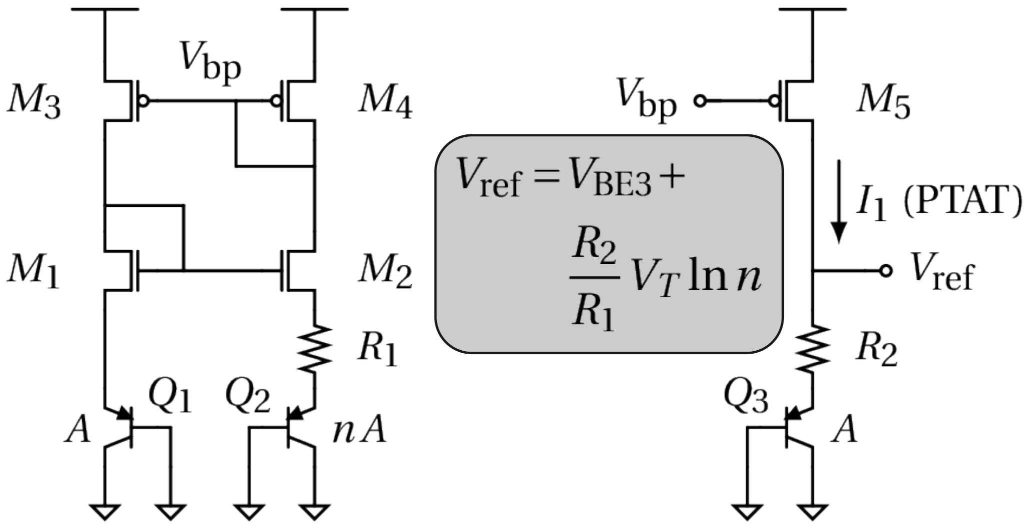
Instead of the diode connected npn that we have used so far, we will use a pnp. This is so that we can implement the device in a CMOS process without any special processing.



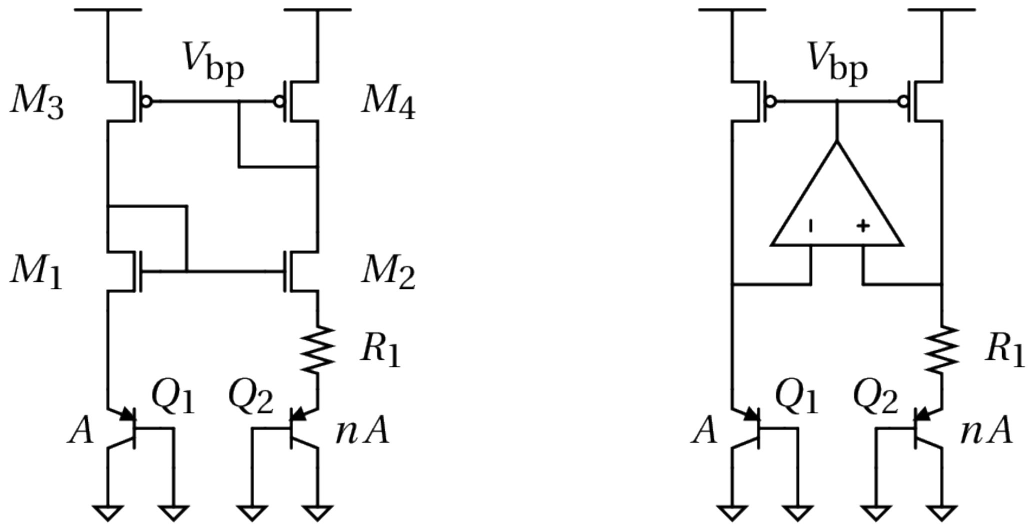
BJT in a CMOS process



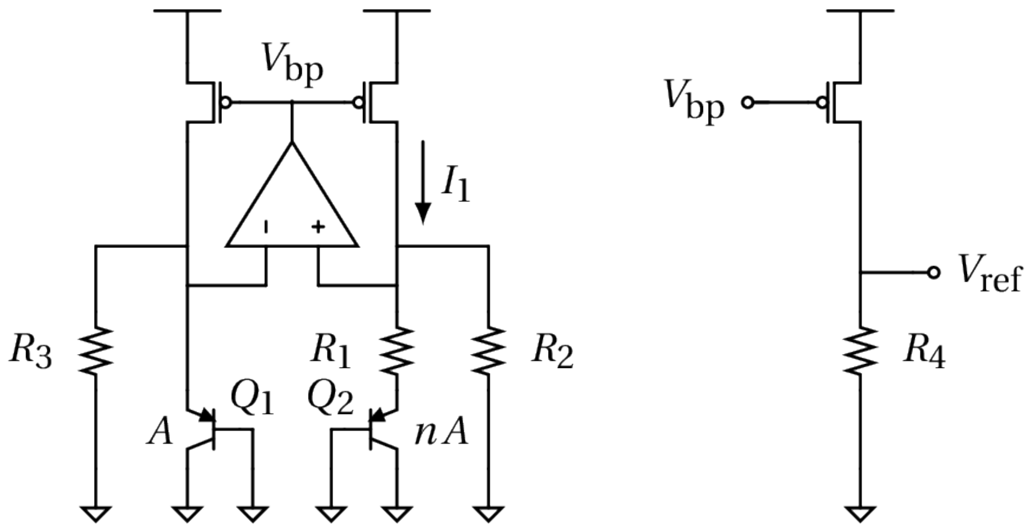
CMOS bandgap



CMOS bandgap



Low-voltage bandgap



Low-voltage bandgap

The core circuit is (again) the PTAT current generator. Although the delta Vbe gives rise to a PTAT voltage (dropped accross R1), the absolute Vbe of Q1 and Q2 is CTAT. Vbe1 controls the current through R2 and R3. The result is a temperature independent current if the currents are scaled correctly.

Low-voltage bandgap

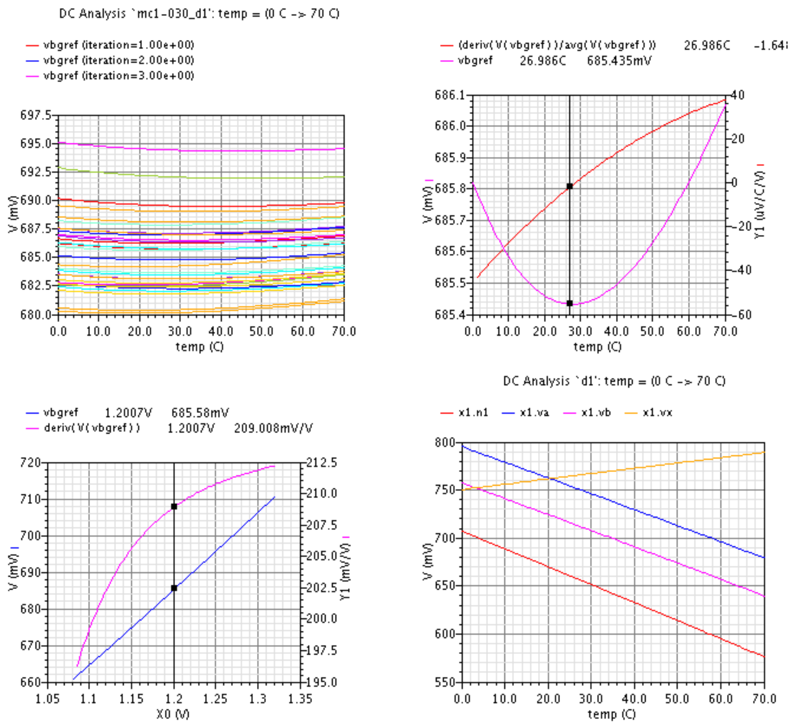
$$I_1 = I_{\text{PTAT}} + I_{\text{CTAT}}$$

$$I_{\text{PTAT}} = \frac{V_T \ln n}{R_1}$$

$$I_{\text{CTAT}} = \frac{V_{\text{BE1}}}{R_3}$$

$$V_{\text{REF}} = R_4 I_1$$

$$= \frac{R_4}{R_1} V_T \ln n + \frac{R_4}{R_3} V_{\text{BE1}}$$



Stability

Stability is a concern for any system with feedback.

Must make sure that we have more negative feedback than positive.

Transient response

Transients may capacitively couple to circuit nodes.

Faster opamp

Decoupling (opamp stability)

Startup circuit

In the discussion so far, we have assumed the circuits are at the desireable operating point.

We must add circuitry to make sure the circuit is not stuck at a "zero" operating point.

Typically a circuit to inject some current if we are at or close to the undesireable operating point. (Power on reset.)

This is very important. Simulator does not neccessarily reveal this problem.

Curvature correction

In our analysis we have asumed the PTAT and CTAT to be constant. This assumption will lead to a non-linearity of the TC (curvature), approximately parabolic shape.

Possible to design some function to try to mitigate this effect.

Even possible to use Vos constructively (Cabrini, ESSCIRC 2005). Not curriculum.

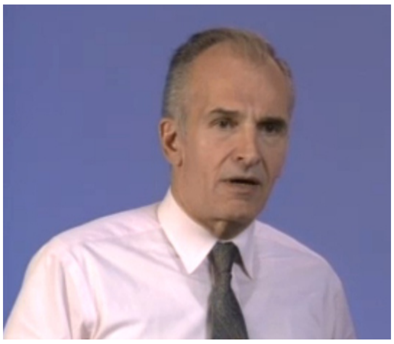
Bandgap circuit issues

- Collector current variation
- CMOS compatibility (BJTs)
- Opamp offset voltage
- Opamp resistive loading
- Stability
- Startup
- Transient response
- PSRR
- Curvature
- Limited supply voltage
- Noise
- Resistor TC

Online resources

This is not part of the curriculum

http://www.archive.org/details/APaulBro1989



A Paul Brokaw