Bandgap Reference Circuit

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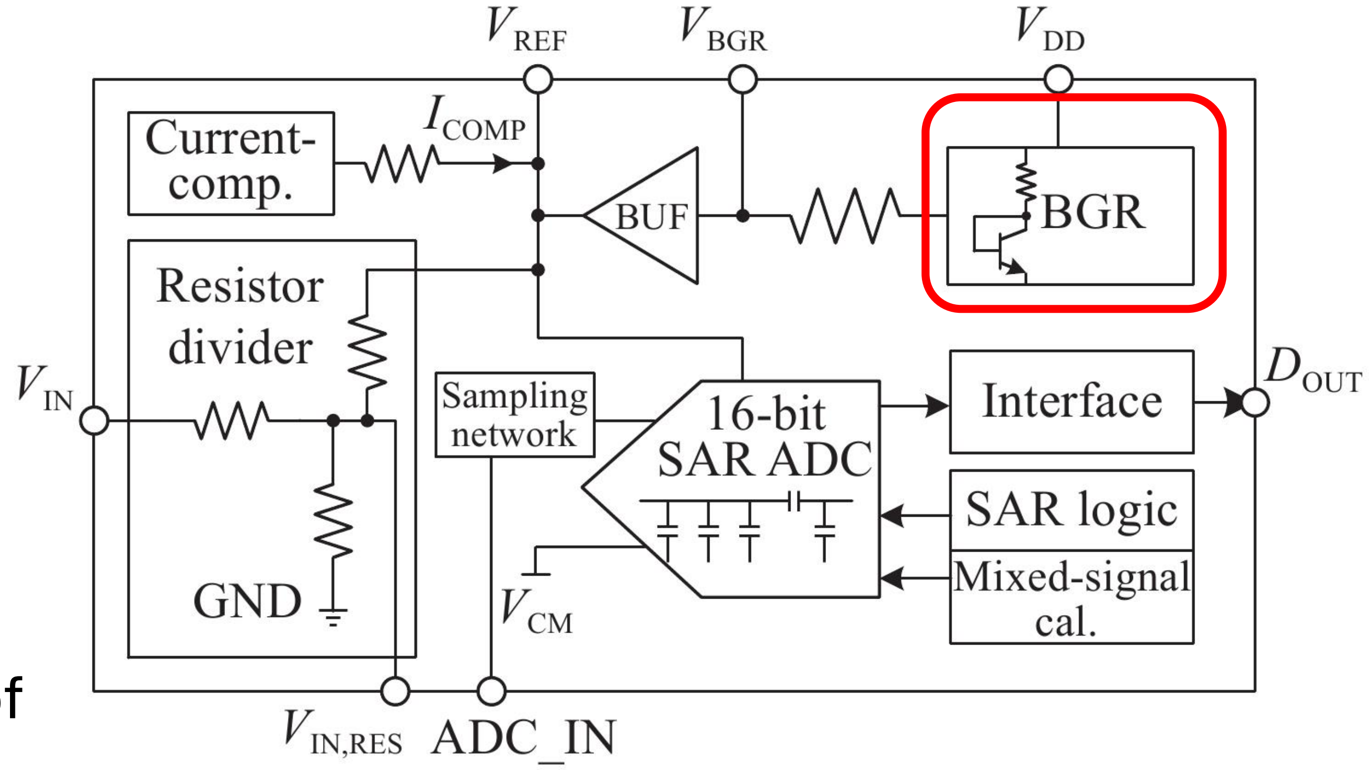
What you can learn

- Note: For optimal viewing experience, please use slideshow mode.

Bandgap Reference (BGR)

- BGR generates a fixed DC reference voltage that does not change with the variation of PVT (Process, Supply Voltage, and Temperature) variation
- Application:
  - Almost everywhere!
    - ADC, DAC,
    - LDO, Sensors,
    - Oscillators (VCO),
    - Precision Analog Circuits

    and many more!!

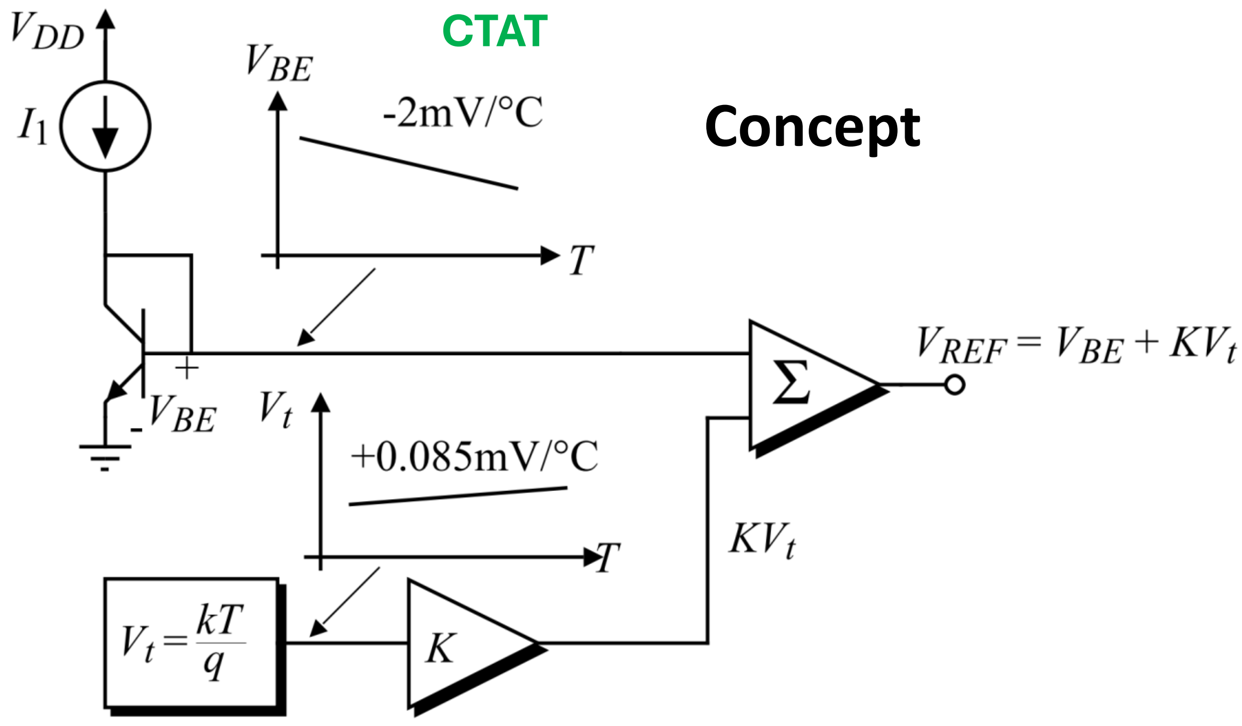


Target: Generate a fixed DC voltage proportional to the Bandgap voltage of silicon.

Bandgap Reference Circuit

- The principle of the bandgap voltage reference
  - Balance the negative temperature coefficient of a pn junction with the positive temperature coefficient of the thermal voltage, Vt = kT/q.
  - In short → Balance V_{BE} with V_T

- Result
  - ▫ Provides “almost” constant voltage across different PVT: $V_{BG} \approx 1.2$ V
- PVT
  - ▫ Process, Voltage and Temperature
  - ▫ SS_1P62_M40C
  - ▫ TT_1P80_25C
  - ▫ FF_1P98_125C

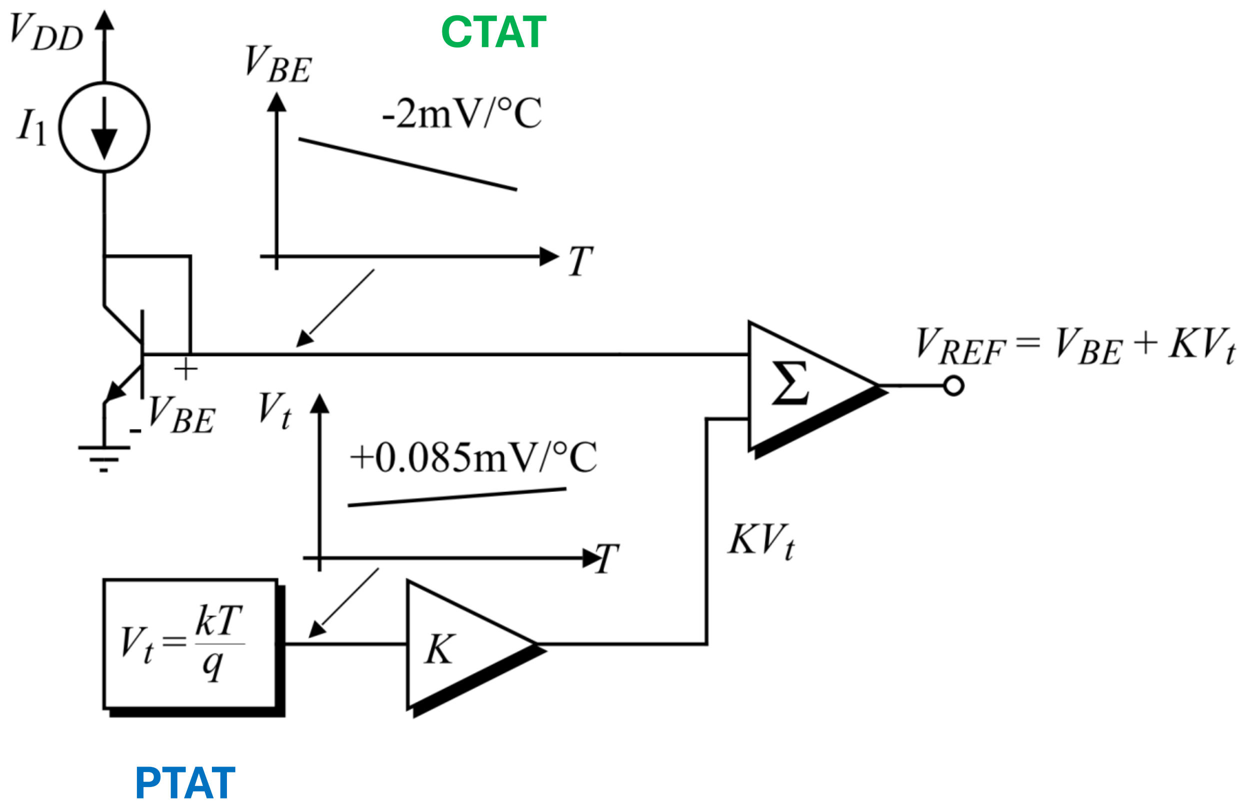


PTAT

[P. E. Allen, 2004]

Effect of Temperature

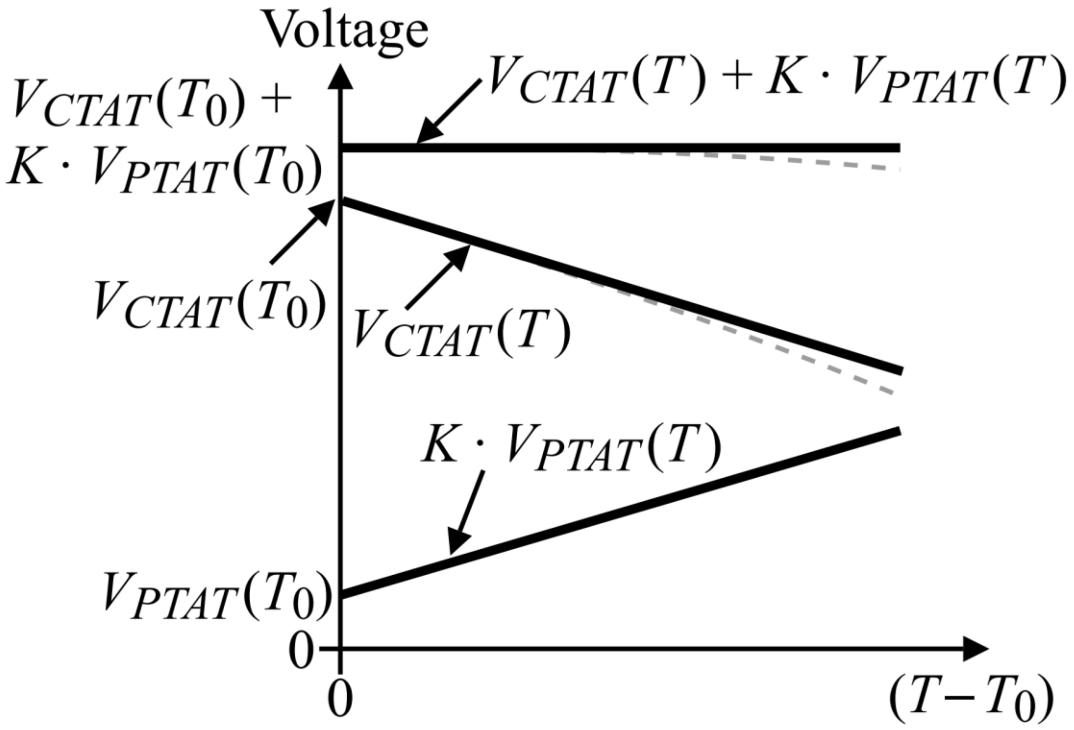
- Two voltages,
  - One that increases proportionately with temperature and is called proportional to absolute temperature or PTAT.
  - One that decreases proportionately with temperature and is called complementary to absolute temperature or CTAT.

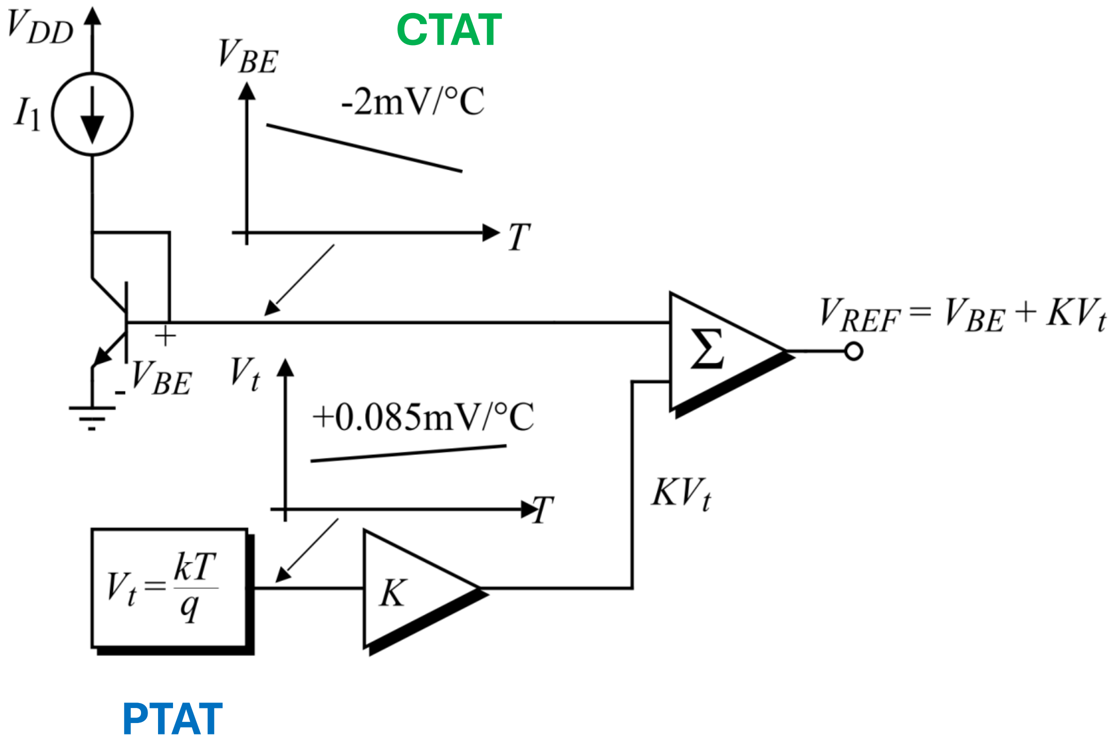


[P. E. Allen, 2004]

Effect of Temperature

- Two voltages,
  - PTAT
  - CTAT
- ZTC (T) = K. PTAT (T) + CTAT (T)





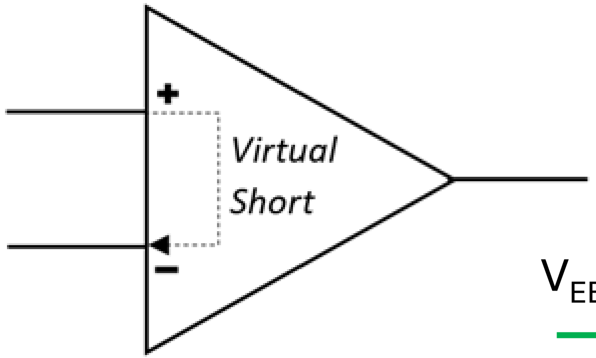
[P. E. Allen, 2004]

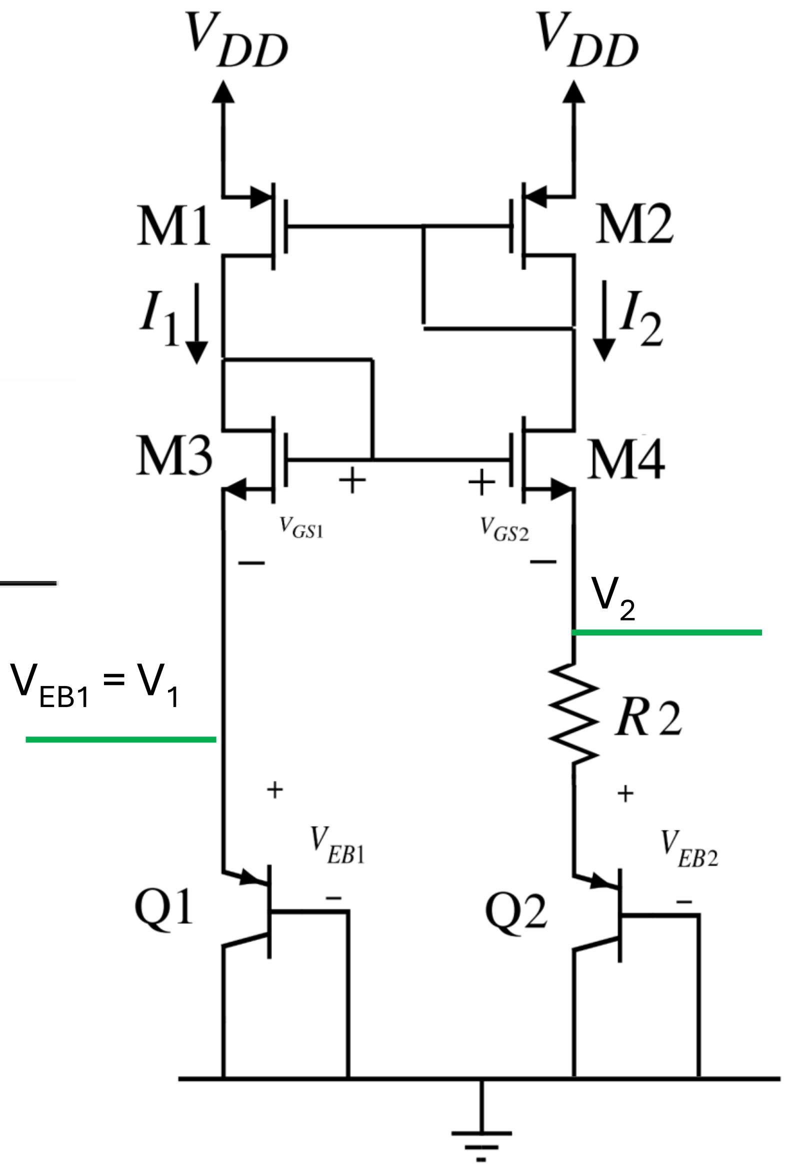
But HOW!!

- Let’s see the basic Bandgap Circuit Structure
- Let’s brush up some concepts
  - “Floating” Current Mirror and “Floater”
  - “Virtual Short” of an OpAmp
  - BJT base-emitter voltage
  - KVL and KCL

Basic Bandgap Circuit

- For the BGR to work
  - $V_1 = V_2$
- How can we make two node voltages equal?
  - Using OpAmp
    - Virtual Short
    - Virtual Ground
    - Asymptotic Equality Principle
  - Using Floating Current Mirror





[P. E. Allen, 2004]

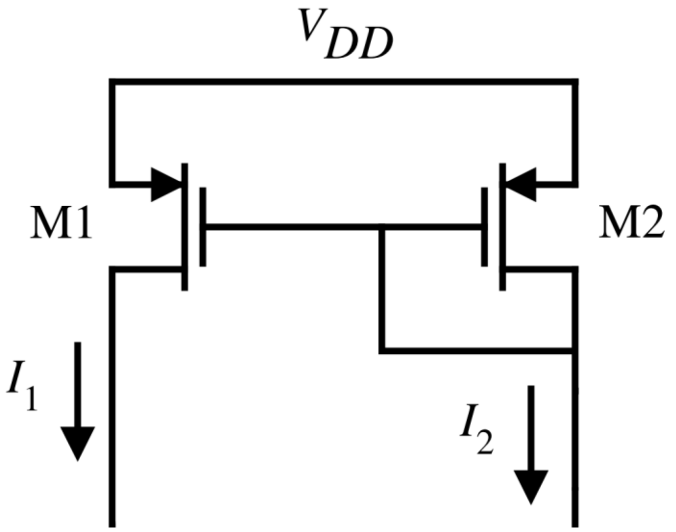
Floating Current Mirror and Floater

Let's Discuss Current Mirror

MOSFET Drain Current Equation:

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (V_{GS} - V_{Th})^2$$

- VGS of M1 and M2 are the same.
  - $V_{GS1} = V_{GS2}$
- Both M1 and M2 are *Identical*
  - $I_2 = I_1$



[P. E. Allen, 2004]

Floating Current Mirror and Floater

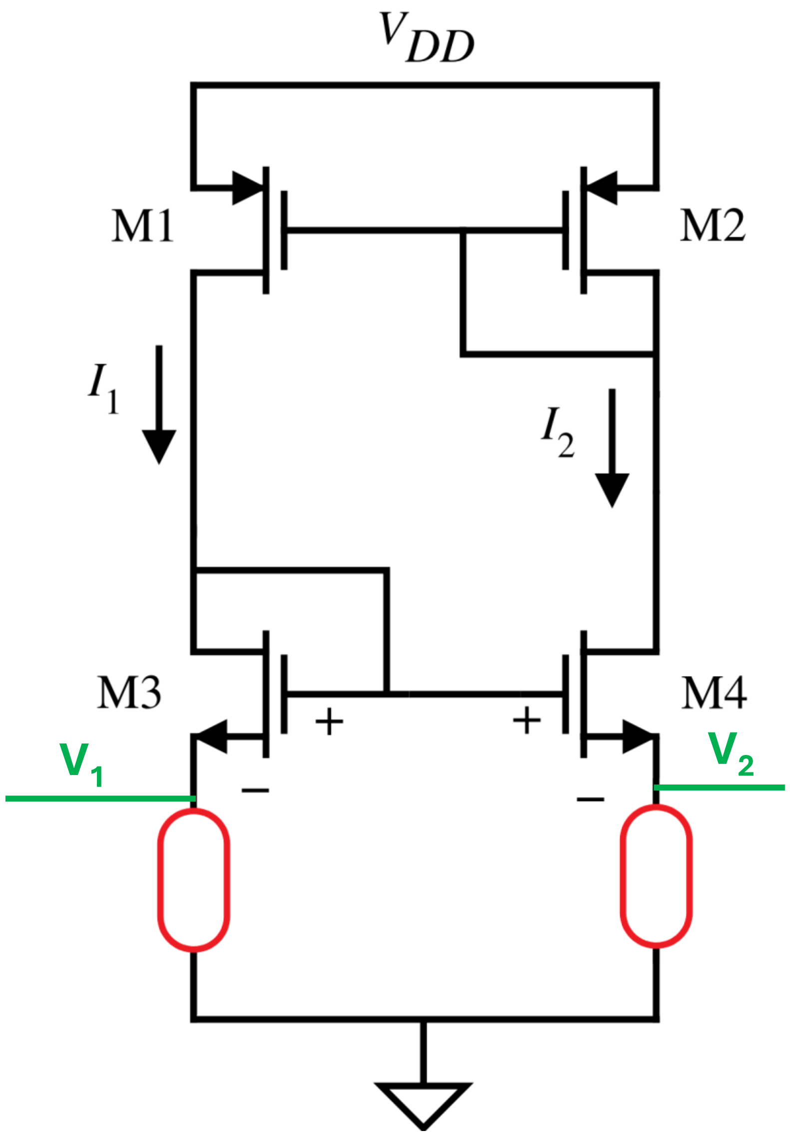
Are the voltages of VGS3 and VGS4 equal irrespective of the load?

In other words, can we force V1 = V2?

MOSFET Drain Current Equation:

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (V_{GS} - V_{Th})^2$$

- Since M1, M2, M3 and M4 are *Identical*
  - I1 = I2
  - VGS1 = VGS2



[P. E. Allen, 2004]

Floating Current Mirror and Floater

Are the voltages of VGS3 and VGS4 equal irrespective of the load?

- Since M1, M2, M3 and M4 are *Identical*
  - I1 = I2

$$I_1 = \frac{\mu_n C_{ox}}{2}\frac{w}{L}(V_{GS3} - V_{Th})^2$$

$$I_2 = \frac{\mu_n C_{ox}}{2}\frac{w}{L}(V_{GS4} - V_{Th})^2$$

$$Since\ I_1 = I_2$$

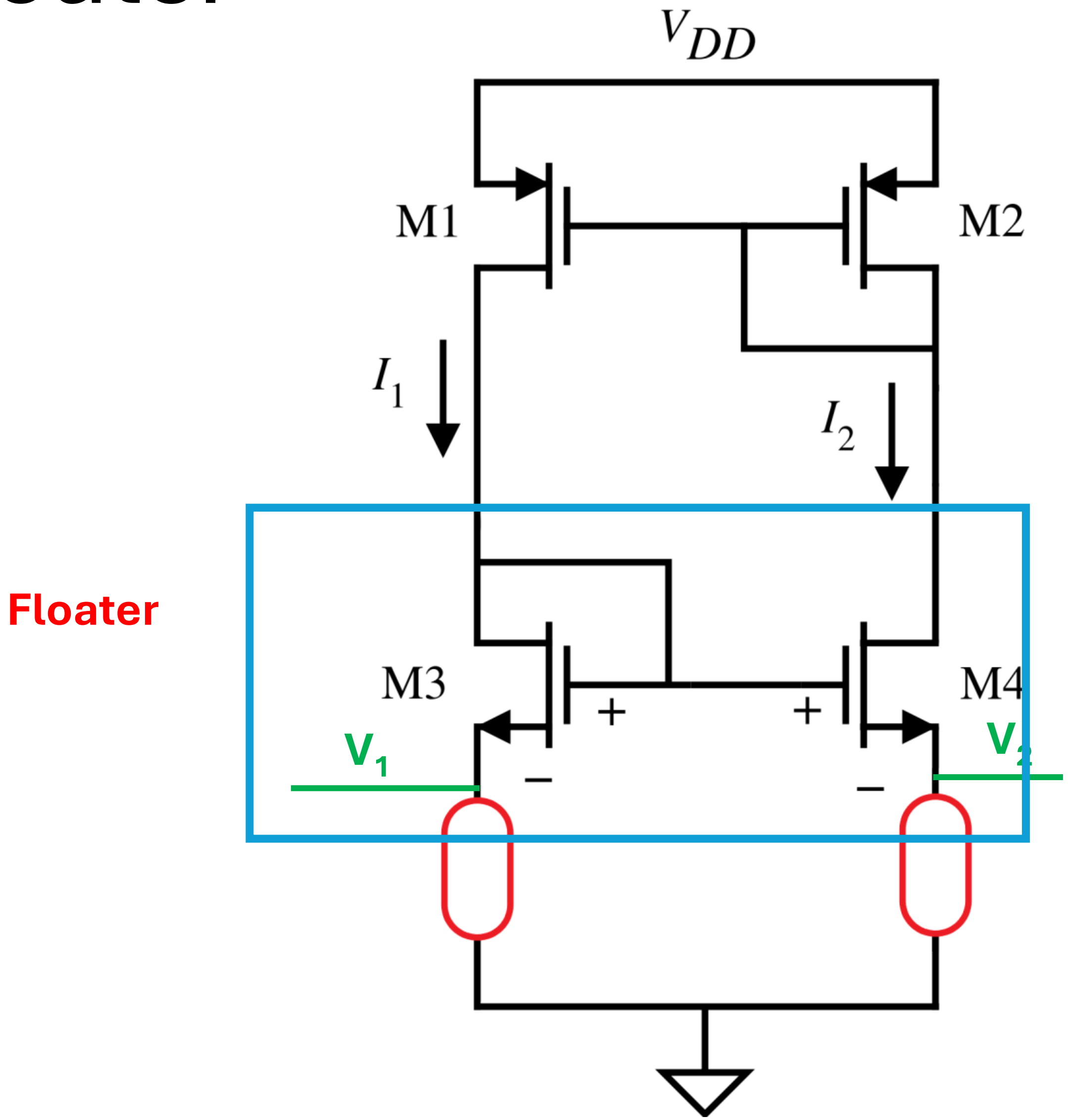
$$\frac{\mu_n C_{ox}}{2}\frac{w}{L}(V_{GS3} - V_{Th})^2 = \frac{\mu_n C_{ox}}{2}\frac{w}{L}(V_{GS4} - V_{Th})^2$$

$$(V_{GS3} - V_{Th})^2 = (V_{GS4} - V_{Th})^2$$

$$V_{GS3} = VGS_4$$

$$V_{S3} = VS_4 [\because VG_3 = VG_4]$$

$$\boldsymbol{V_1 = V_2}$$



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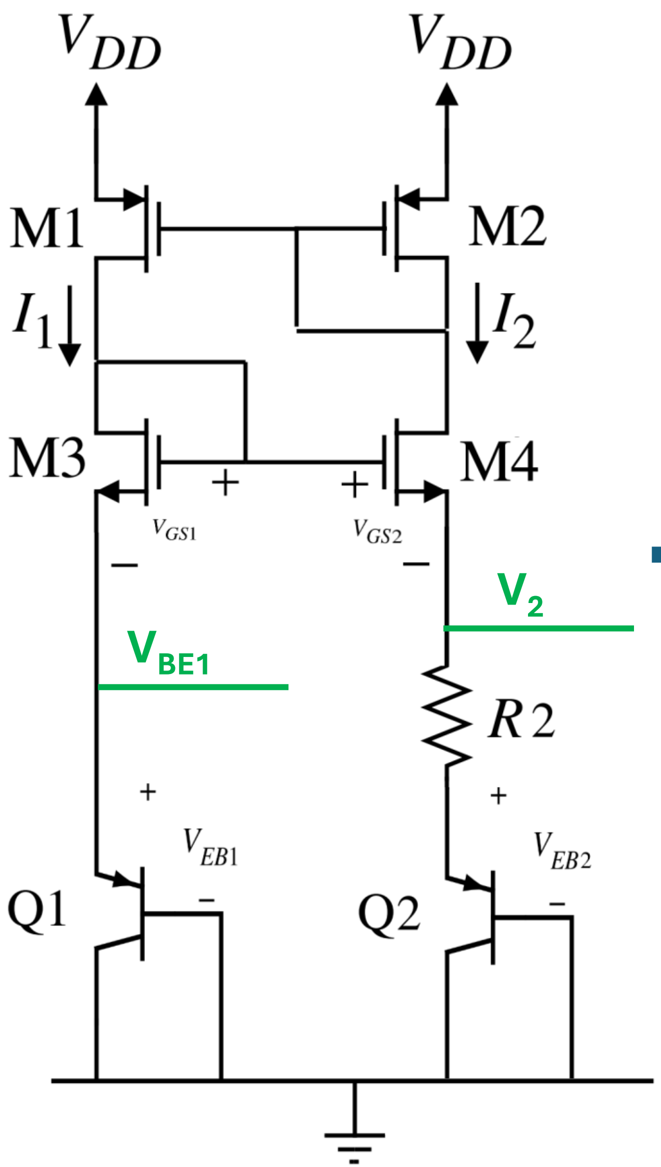
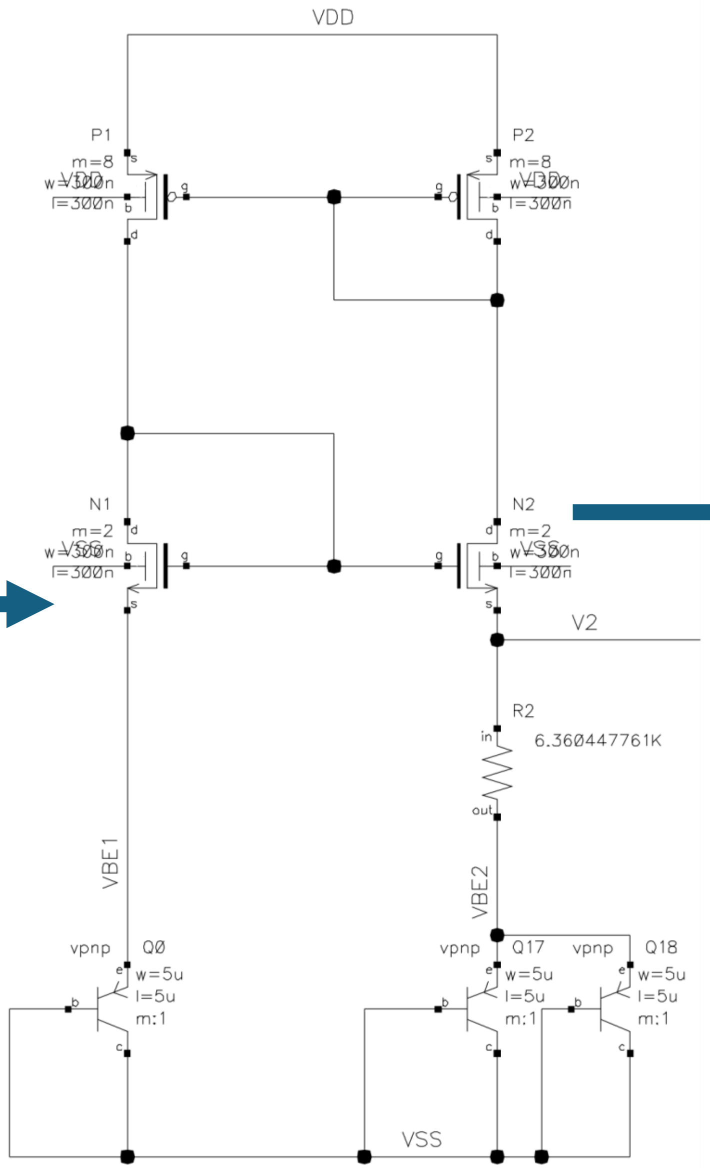
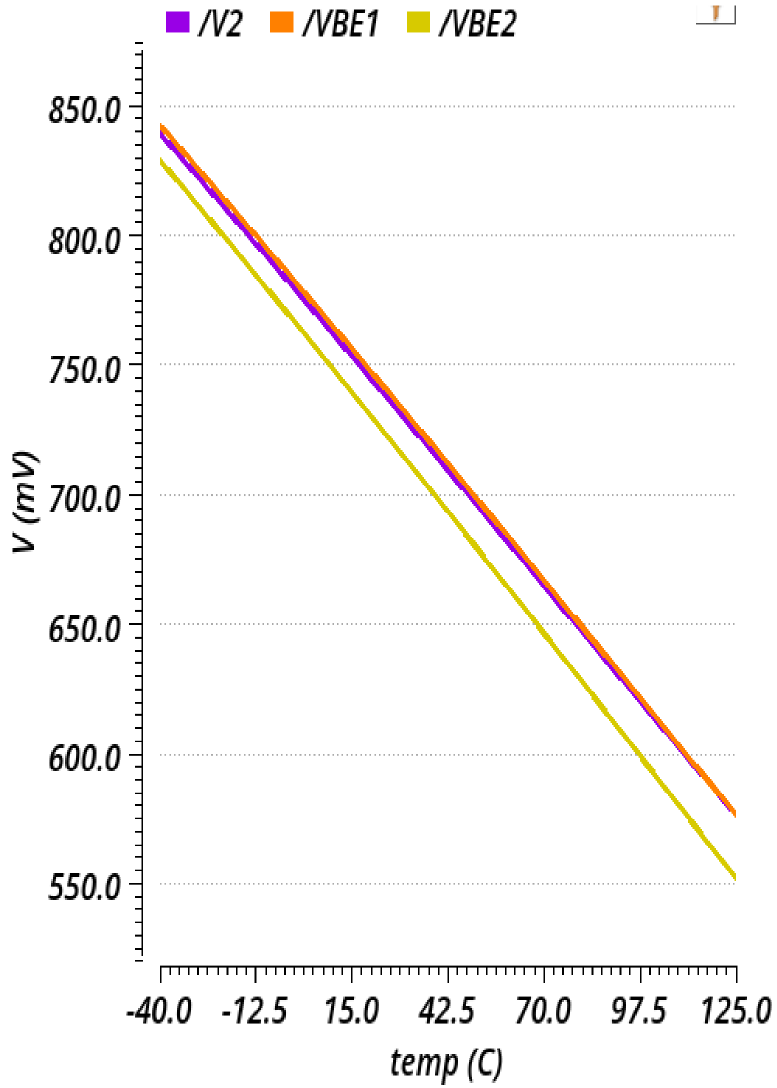
Concept Checkpoint

Note: VDD = 1.8V, VSS = 0V





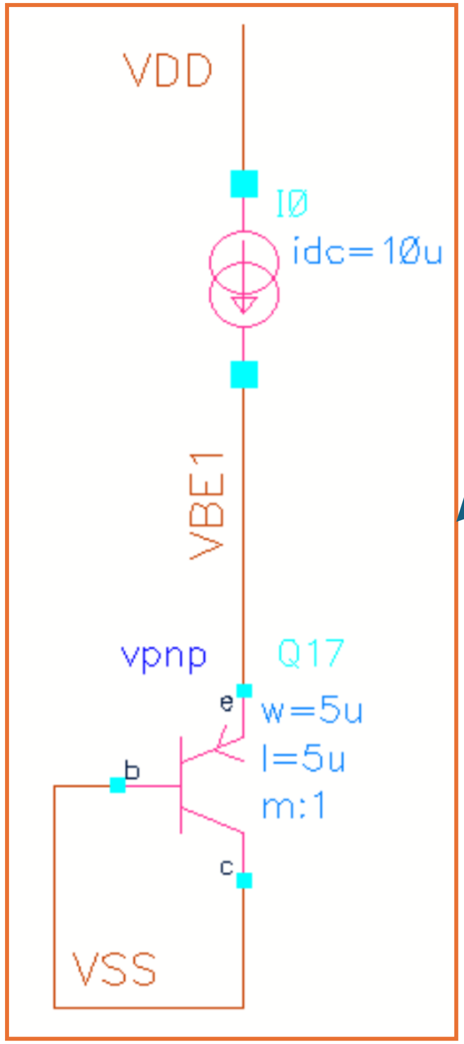


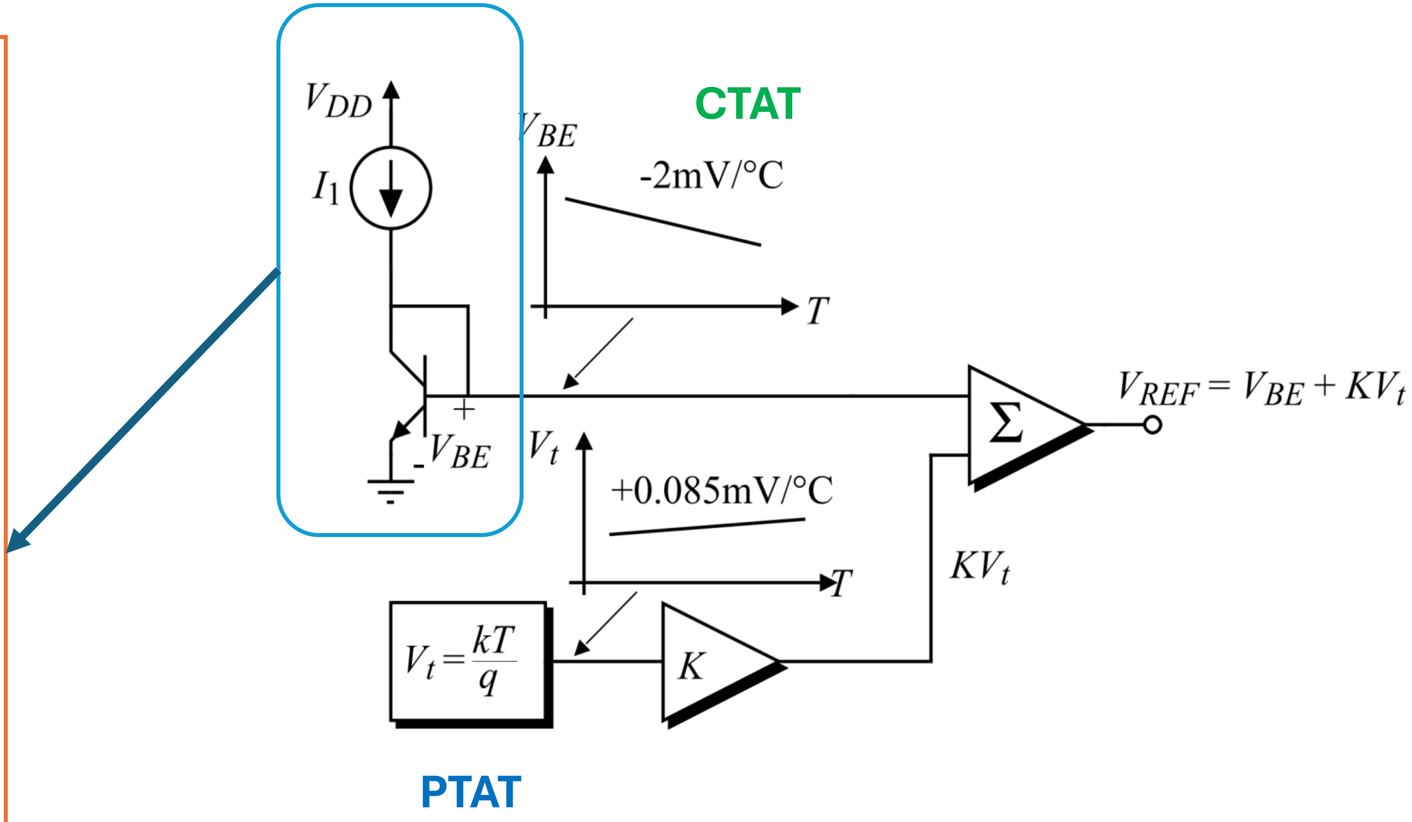
VBE of BJT

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_s}\right)$$

$$V_{BE} = \boxed{\frac{kT}{q}} \ln\left(\frac{I_C}{I_s}\right)$$

Isn't $V_{BE} \propto T$??





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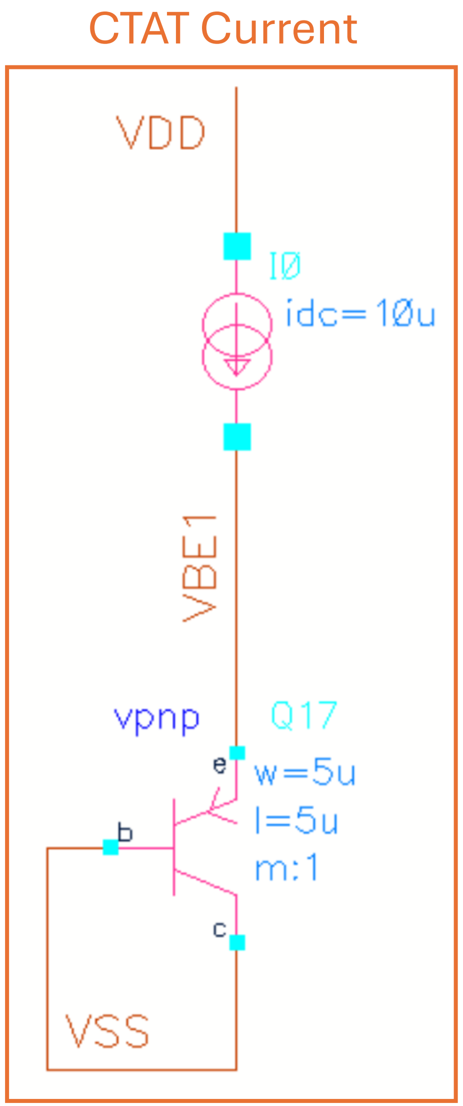
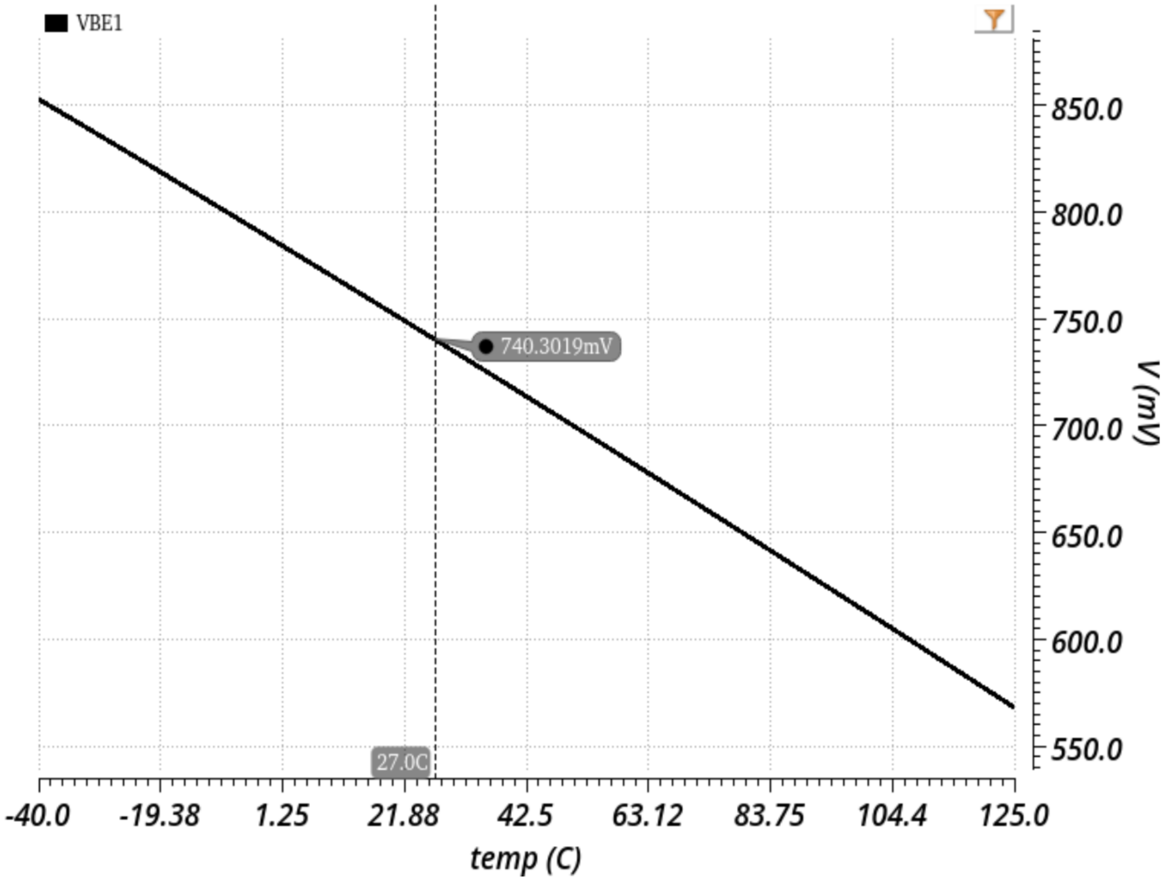
Let’s Do a simulation!



Sweep the temp from -40°C to 125°C



$$V_{BE} = \boxed{\frac{kT}{q}} \ln\left(\frac{I_C}{I_s}\right)$$

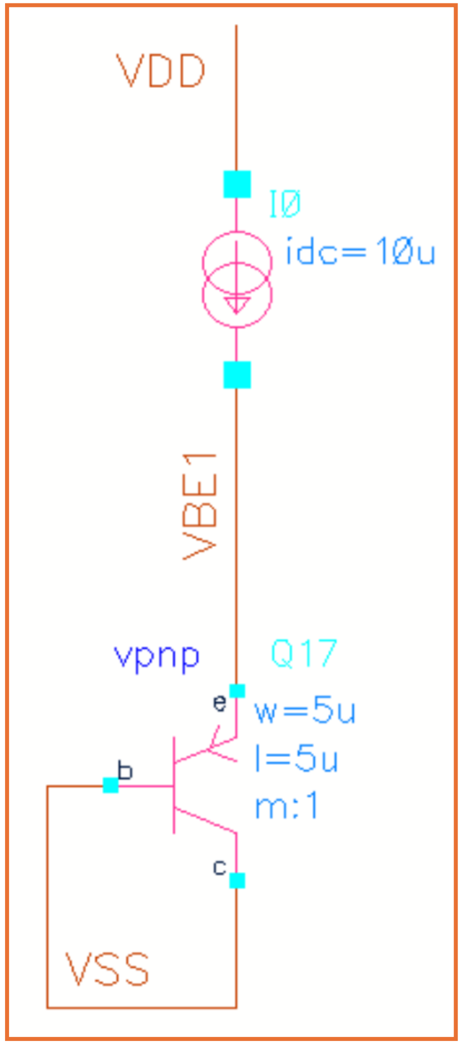
Why is the voltage decreasing?

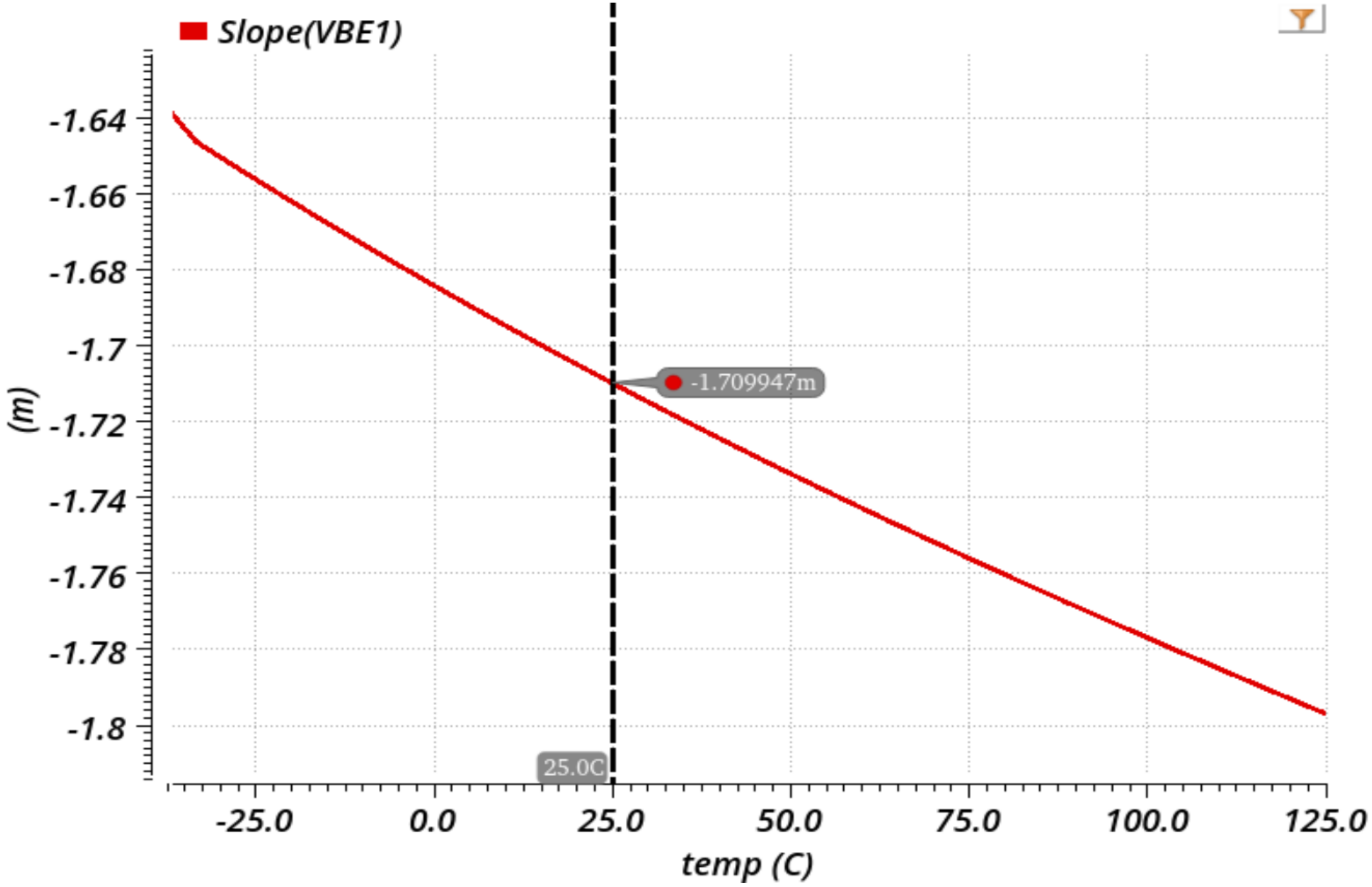
$$V_{BE} = \frac{kT}{q} \ln\left(\frac{I_C}{\boxed{I_s}}\right)$$

VBE of BJT as CTAT

Sweep the temp from -40°C to 125°C

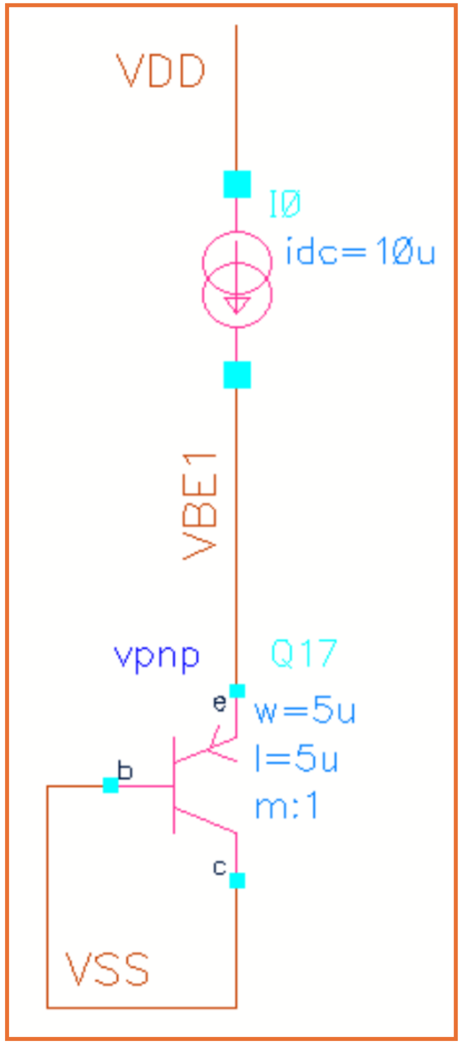
CTAT Current





VBE of BJT as CTAT

CTAT Current



$$V_{BE} = \frac{kT}{q} \ln \left(\frac{I_C}{\boxed{I_s}} \right)$$

- I_s has such an incredibly strong temp dependence that even through the log it overwhelms the proportional Temp dependence!
- Let’s see HOW!

VBE of BJT as CTAT

$$V_{BE} = \frac{kT}{q} \ln\left(\frac{I_C}{I_S}\right)$$

I_S = Saturation Current of BJT

$$I_S = \frac{qAn_i^2 D}{WN_A}$$

Where,

q = Electron Charge (Constant)

A = Area of Emitter (Constant at 1st order)

W = Width of Base(Constant at 1st order)

N_A = Doping Concentration (Constant)

D = Diffusion Constant (NOT CONSTANT)

n_i^2 = Number of intrinsic carrier concentration

$$D = \frac{kT}{q}\,\mu$$

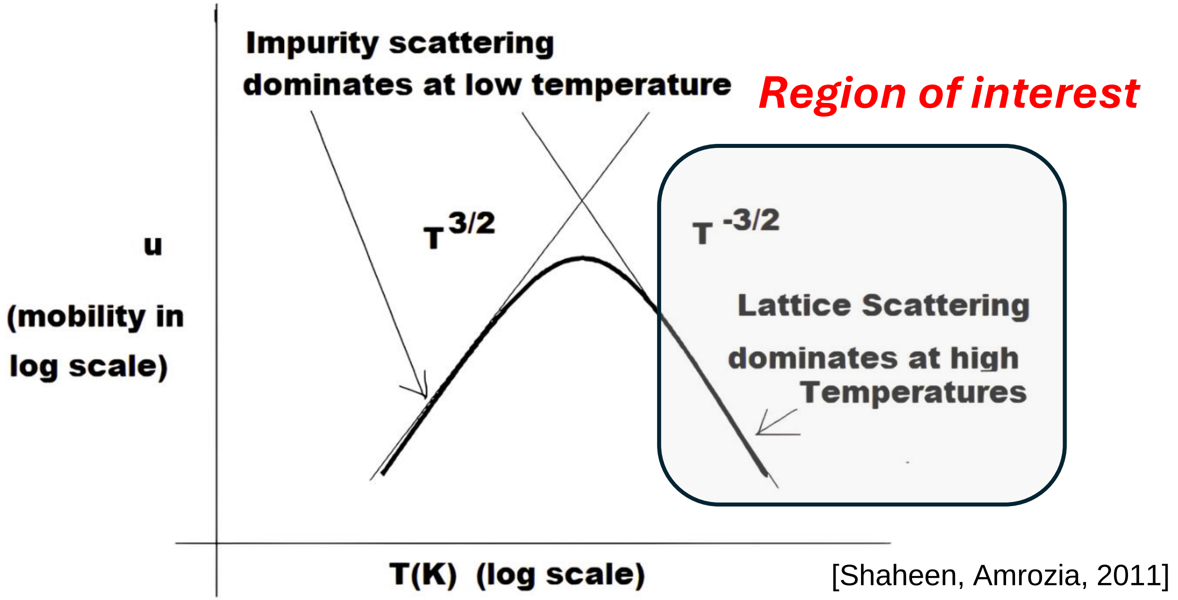


Figure. Temperature dependence of mobility in Si.

$$D = \frac{kT}{q}\,\mu = \frac{kT}{q}\,T^{-3/2}$$

$$n_i^2 = D' T^3 e^{-\frac{V_{BG}}{V_T}}$$

VBE of BJT as CTAT

$$V_{BE} = \frac{kT}{q} \ln\left(\frac{I_C}{I_s}\right)$$

$$I_S = \frac{qAn_i^2 D}{WN_A}$$

$$n_i^2 = D' T^3 e^{-\frac{V_{BG}}{V_T}}$$

$$D = \frac{kT}{q} \mu$$

$$= \frac{kT}{q} T^{-3/2}$$

$$I_S = \frac{qA\left(D' T^3 e^{-\frac{V_{BG}}{V_T}}\right) \frac{kT}{q} T^{-3/2}}{WN_A}$$

$$I_S = E \cdot T^3 \cdot T \cdot T^{-\frac{3}{2}} e^{-\frac{V_{BG}}{V_T}}$$

$$\boxed{I_S = E \cdot T^{\frac{5}{2}} e^{-\frac{V_{BG}}{V_T}}}$$

VBE of BJT as CTAT

$$I_S = E \cdot T^{\frac{5}{2}} e^{-\frac{V_{BG}}{V_T}}$$

$$\boxed{V_{BE} = \frac{kT}{q} \ln\left(\frac{I_C}{I_s}\right)}$$

Overall CTAT

Can we use MOSFET to achieve CTAT?

No. Since the Electrical Behavior of MOSFET is heavily process Dependent!

$$V_{BE} = \frac{kT}{q} \ln(I_c) - \frac{kT}{q} \ln(I_s)$$

$$V_{BE} = \frac{kT}{q} \ln(I_c) - \frac{kT}{q} \ln(E) - \frac{5}{2}\frac{kT}{q} \ln(T) + \cancel{\frac{kT}{q}} \cdot \frac{V_{BG}}{\cancel{V_T}}$$

$$\boldsymbol{V_{BE}} = \underbrace{\frac{kT}{q} \ln(I_c)}_{\text{Weak PTAT}} \underbrace{- \boldsymbol{\frac{kT}{q} \ln(E)} - \boldsymbol{\frac{5}{2}\frac{kT}{q} \ln(T)}}_{\text{Strong CTAT}} + \underbrace{V_{BG}}_{\text{Constant BG voltage}}$$

Base-Emitter Voltage of BJT

$$V_{BE} = \underbrace{\frac{kT}{q}\ln(I_c)}_{\text{Weak PTAT}} \underbrace{- \frac{kT}{q}\ln(E) - \frac{5}{2}\frac{kT}{q}\ln(T)}_{\text{Strong CTAT}} + \underbrace{V_{BG}}_{\text{Constant BG voltage}}$$

- Overall Negative Temp coefficient
- Directly related to the Bandgap voltage (V_{BG})
  - Bandgap voltage is an intrinsic property of a semiconductor
  - It doesn’t depend on PVT variation, and this is what we want!
  - Our target is to get this voltage and use that as a way of making a voltage reference!

Idea of BGR

$$V_{BE} = \underbrace{\frac{kT}{q}\ln(I_c)}_{\text{Weak PTAT}} \underbrace{- \frac{kT}{q}\ln(E) - \frac{5}{2}\frac{kT}{q}\ln(T)}_{\text{Strong CTAT}} + \underbrace{V_{BG}}_{\text{Constant BG voltage}}$$

- Increase "Weak PTAT" to be equal to "Strong CTAT"
  - They will cancel each other!
  - Mathematically: ZTC (T) = K. PTAT (T) + CTAT (T)
- We'll be left with a CONSTANT Bandgap Voltage
  - For Silicon it is approximately 1.2 V

Idea of BGR

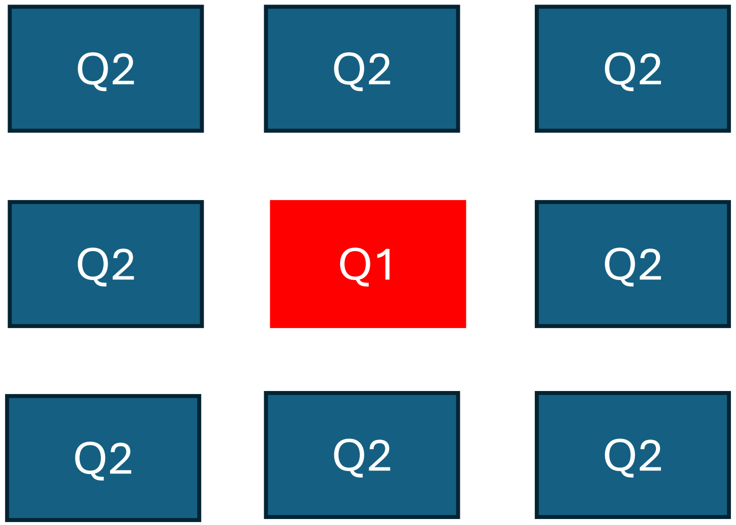
$$\boldsymbol{V_{BE}} = \underbrace{\frac{kT}{q}\ln(I_c)}_{\text{Weak PTAT}} \underbrace{- \frac{\boldsymbol{kT}}{\boldsymbol{q}}\mathbf{ln}(\boldsymbol{E}) - \frac{\mathbf{5}}{\mathbf{2}}\frac{\boldsymbol{kT}}{\boldsymbol{q}}\mathbf{ln}(\boldsymbol{T})}_{\text{Strong CTAT}} + \underbrace{V_{BG}}_{\text{Constant BG voltage}}$$

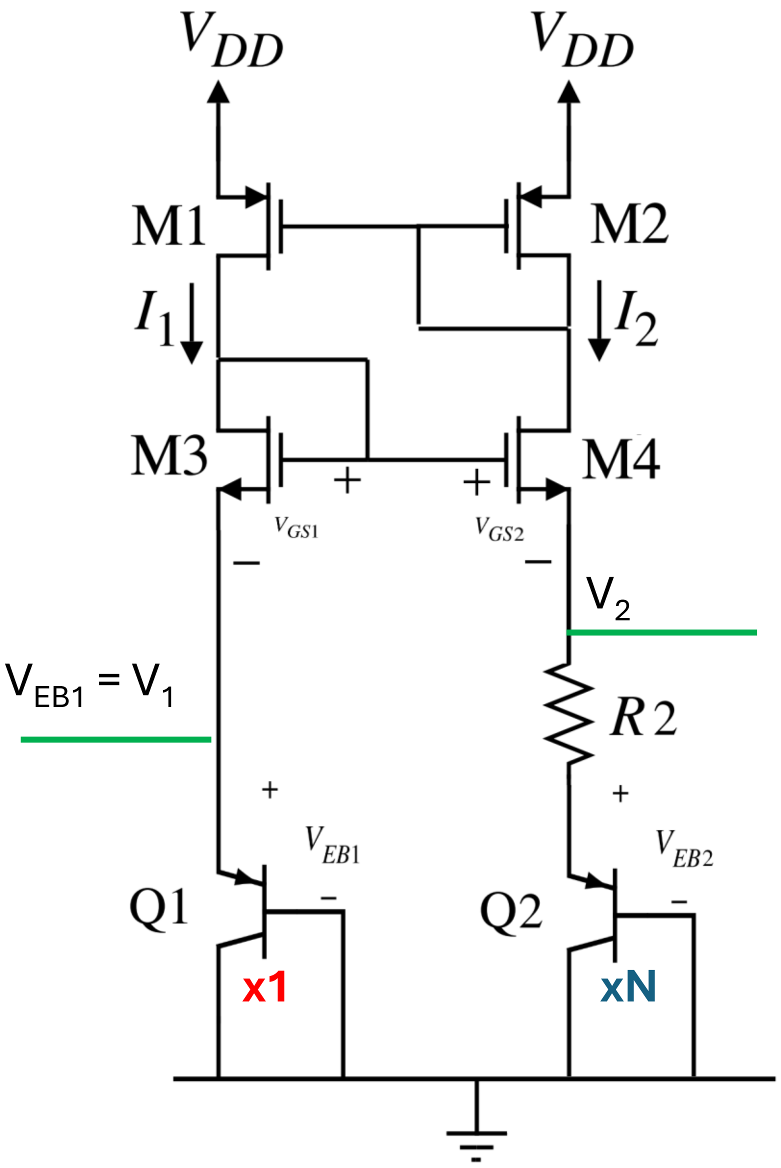
$$V_{BE} = \underbrace{\frac{kT}{q}}_{\text{Weak PTAT}}\underbrace{\ln\left(\frac{I_C}{I_s}\right)}_{\text{Strong CTAT}}$$

- But first of all, We need to extract "Weak PTAT" from V_{BE}!
  - How can we do that?

Choice of N (Making PTAT Stronger)

- Usually the value of "N" is chosen such a way to make N = integer^2 – 1
- For example, N= 8 (3^2 – 1)
- Why??
- Because of matching in layout. E.g. Common-centroid matching



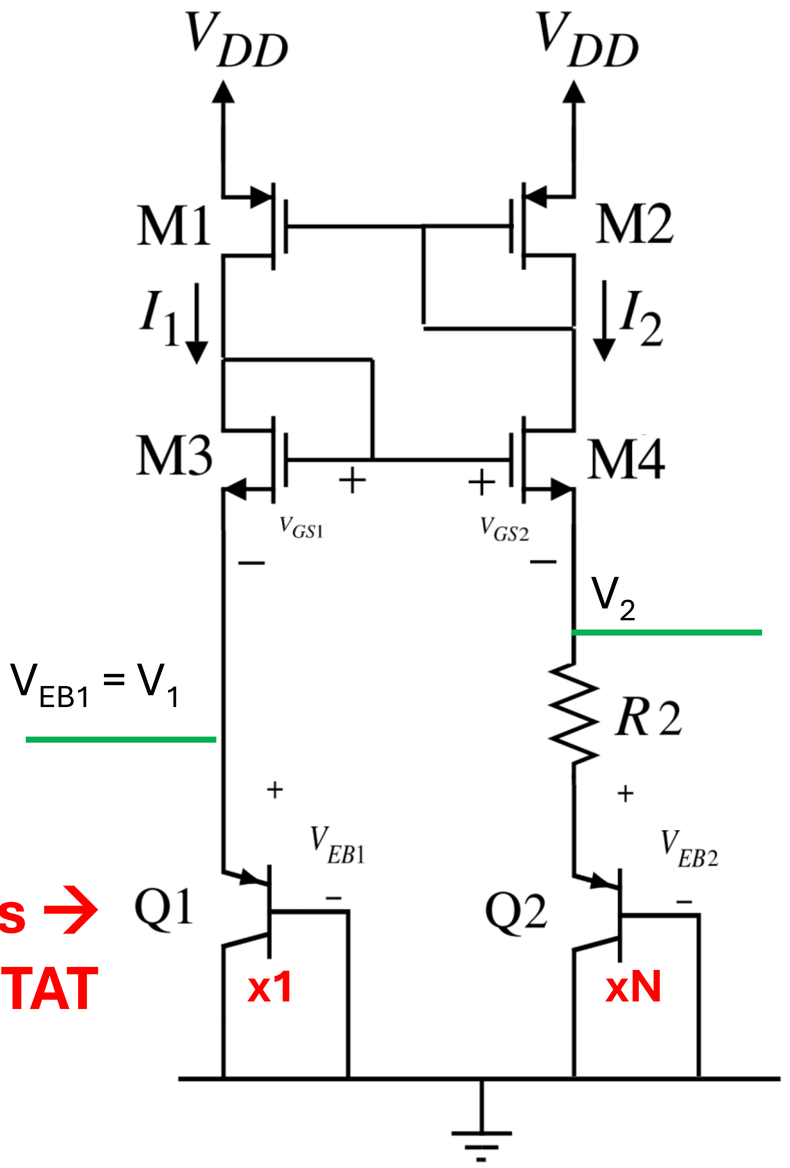


[P. E. Allen, 2004]

Extracting PTAT

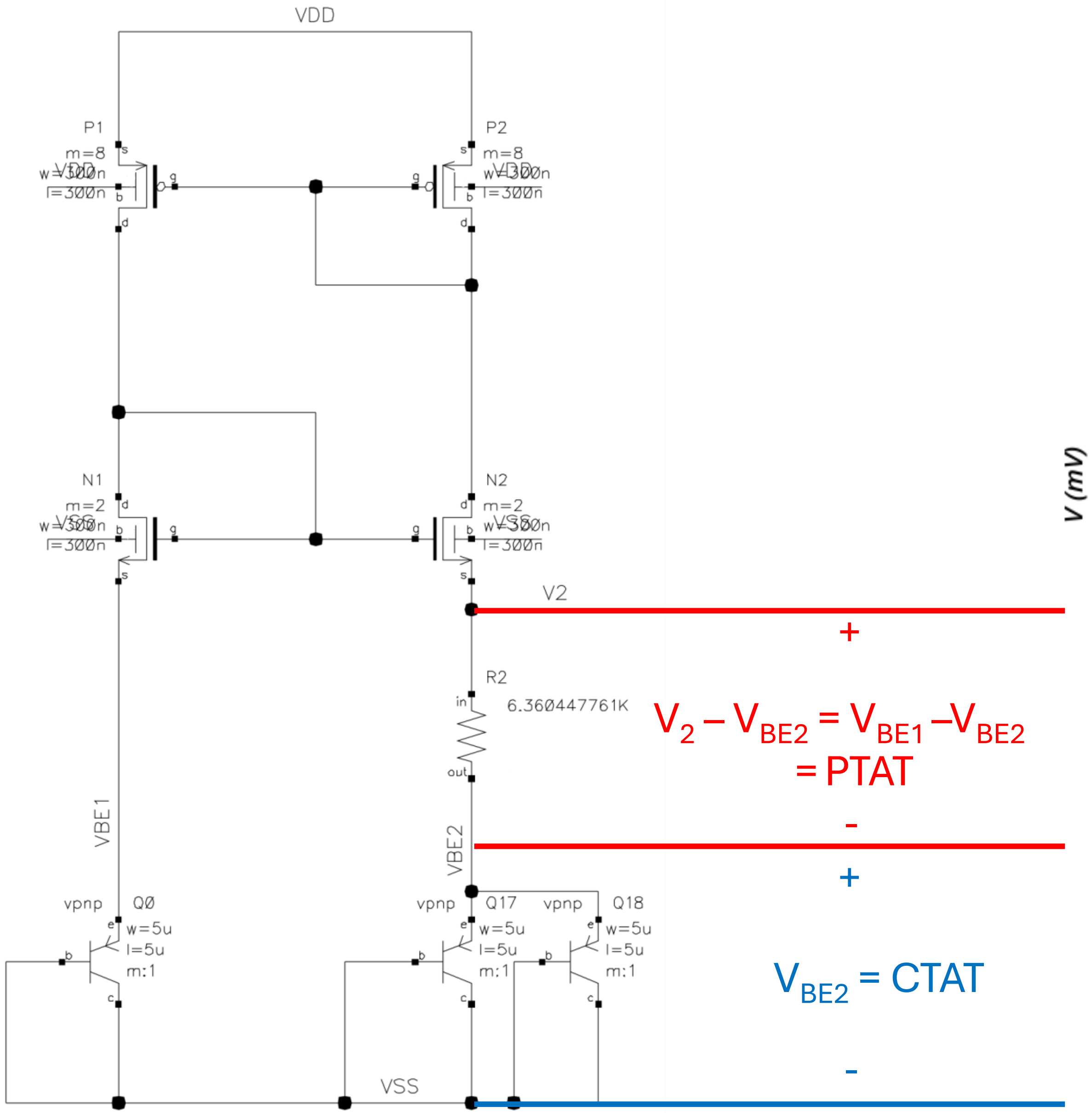
- Make I1 = I2 = I and V1 = V2 using current mirror or OpAmp
- $V_{BE1} = RI + V_{BE2}$
- $V_{BE1} - V_{BE2} = RI$
- $\frac{kT}{q}\ln\left(\frac{I_C}{I_S}\right) - \frac{kT}{q}\ln\left(\frac{I_C}{NI_S}\right) = RI$ [Assuming identical BJT]
- $\frac{kT}{q}\ln(N) = \text{RI}$
- $\text{I} = \frac{k\mathbf{T}}{qR}\ln(N)$

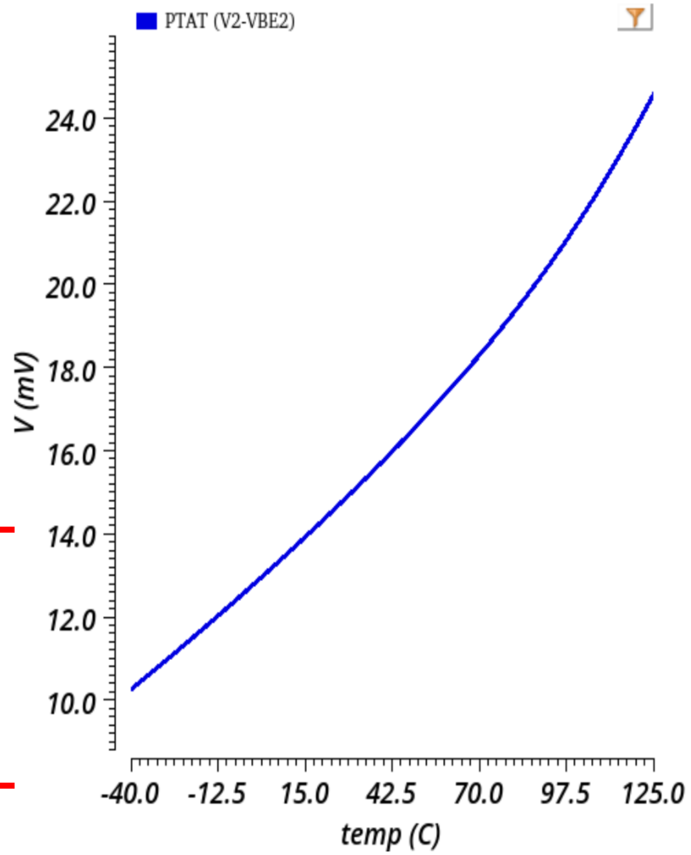
PTAP Current
→ Use CM to generate multiple copies → Drop it across a resistor to generate PTAT Voltage

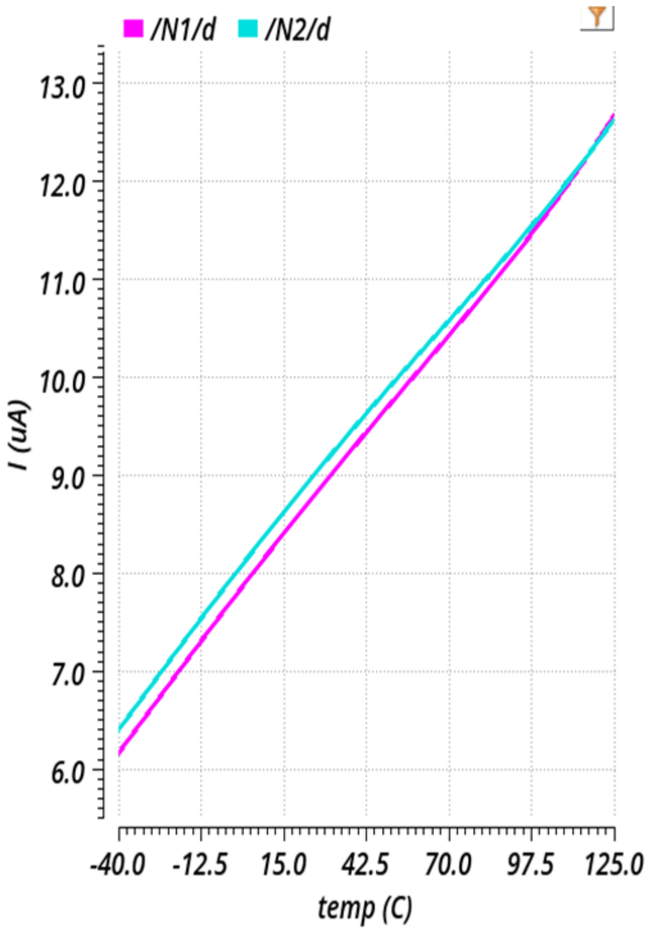


[P. E. Allen, 2004]

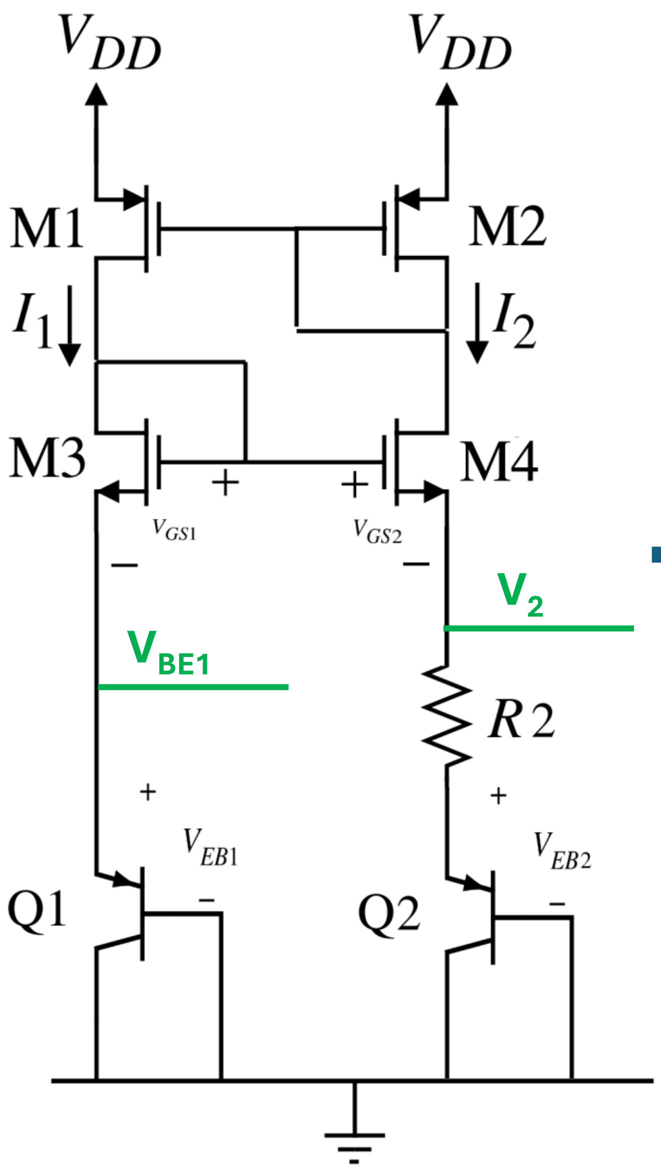
Simulation Verification of PTAT Current and Voltage



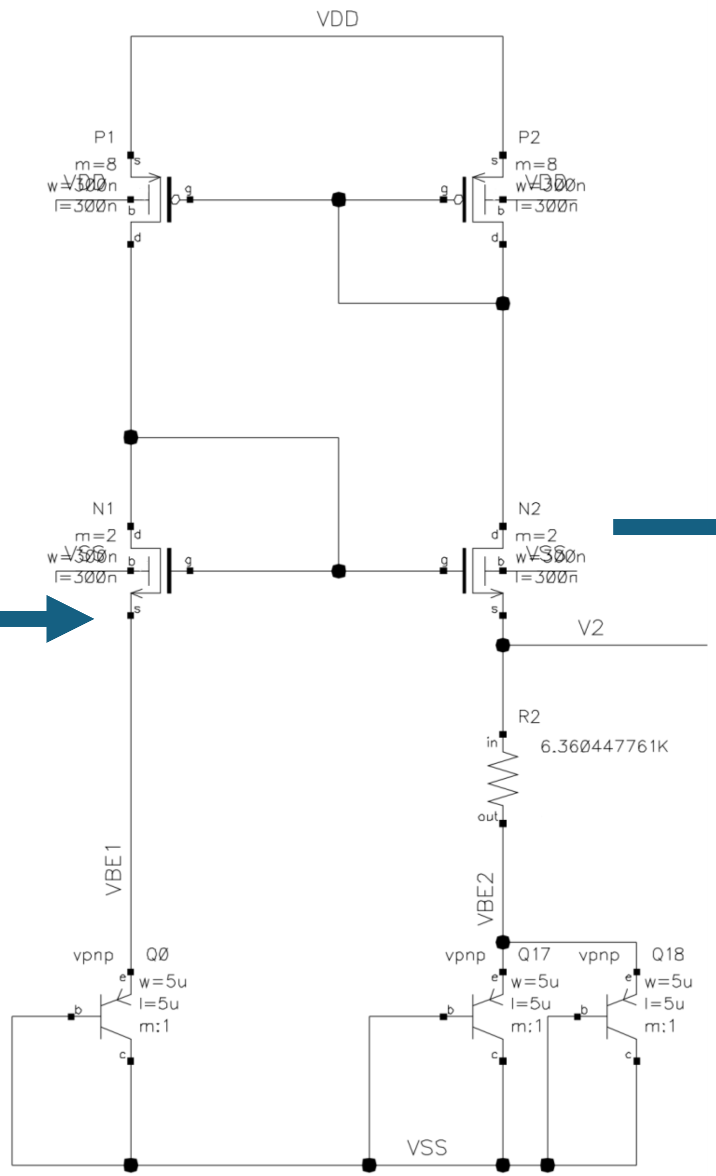




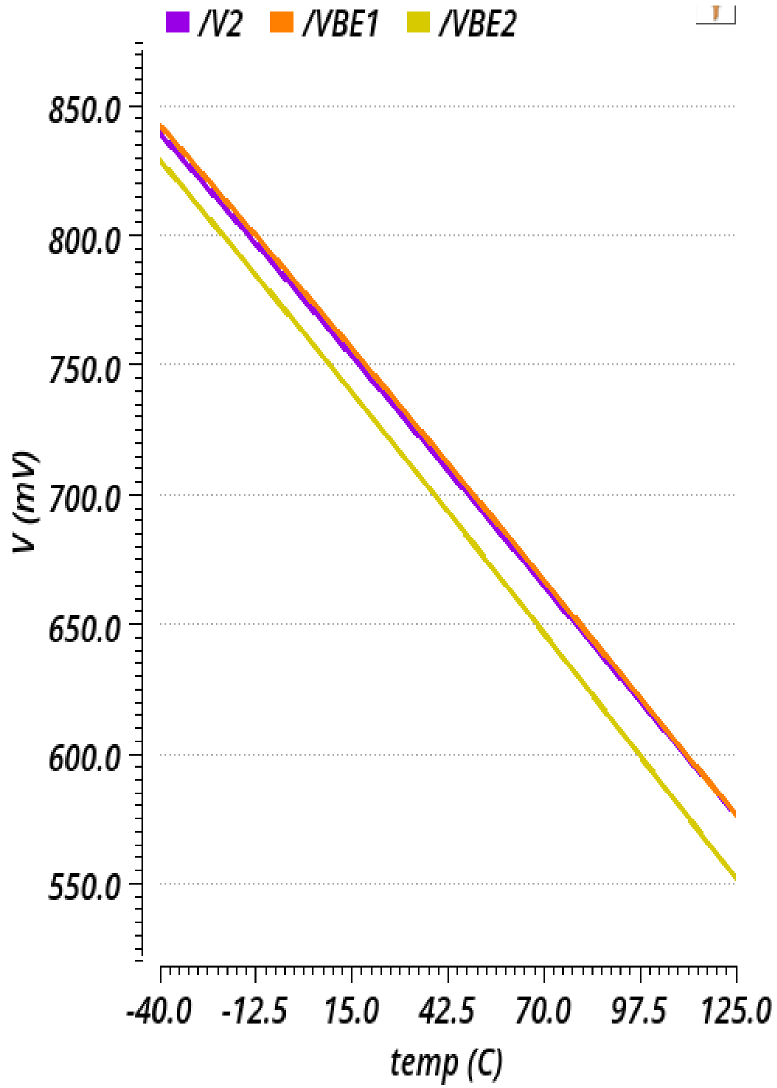
Review: CTAT



V_{DD}
V_{DD}
M1
M2
I_1
I_2
M3
M4
V_{GS1}
V_{GS2}
V_{BE1}
V_2
$R2$
V_{EB1}
V_{EB2}
Q1
Q2



VDD
P1
m=8
w=300n
l=300n
P2
m=8
w=300n
l=300n
N1
m=2
w=300n
l=300n
N2
m=2
w=300n
l=300n
V2
R2
6.360447761K
VBE1
VBE2
vpnp Q0
w=5u
l=5u
m:1
vpnp Q17
w=5u
l=5u
m:1
vpnp Q18
w=5u
l=5u
m:1
VSS



/V2
/VBE1
/VBE2
V (mV)
850.0
800.0
750.0
700.0
650.0
600.0
550.0
-40.0
-12.5
15.0
42.5
70.0
97.5
125.0
temp (C)

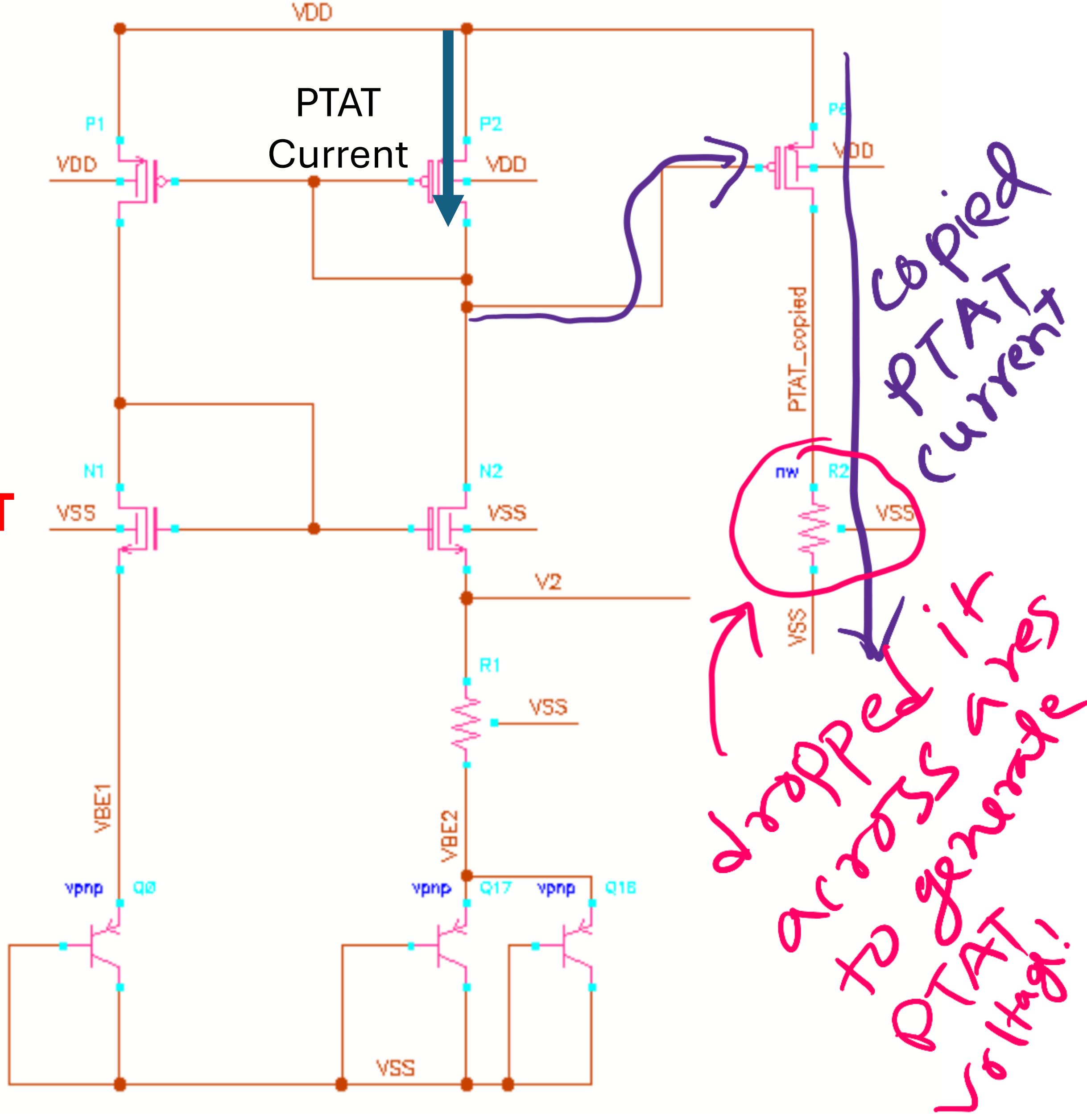
Extracting PTAT Voltage Separately

$$I_{PTAT} = \frac{kT}{qR}\ln(N)$$

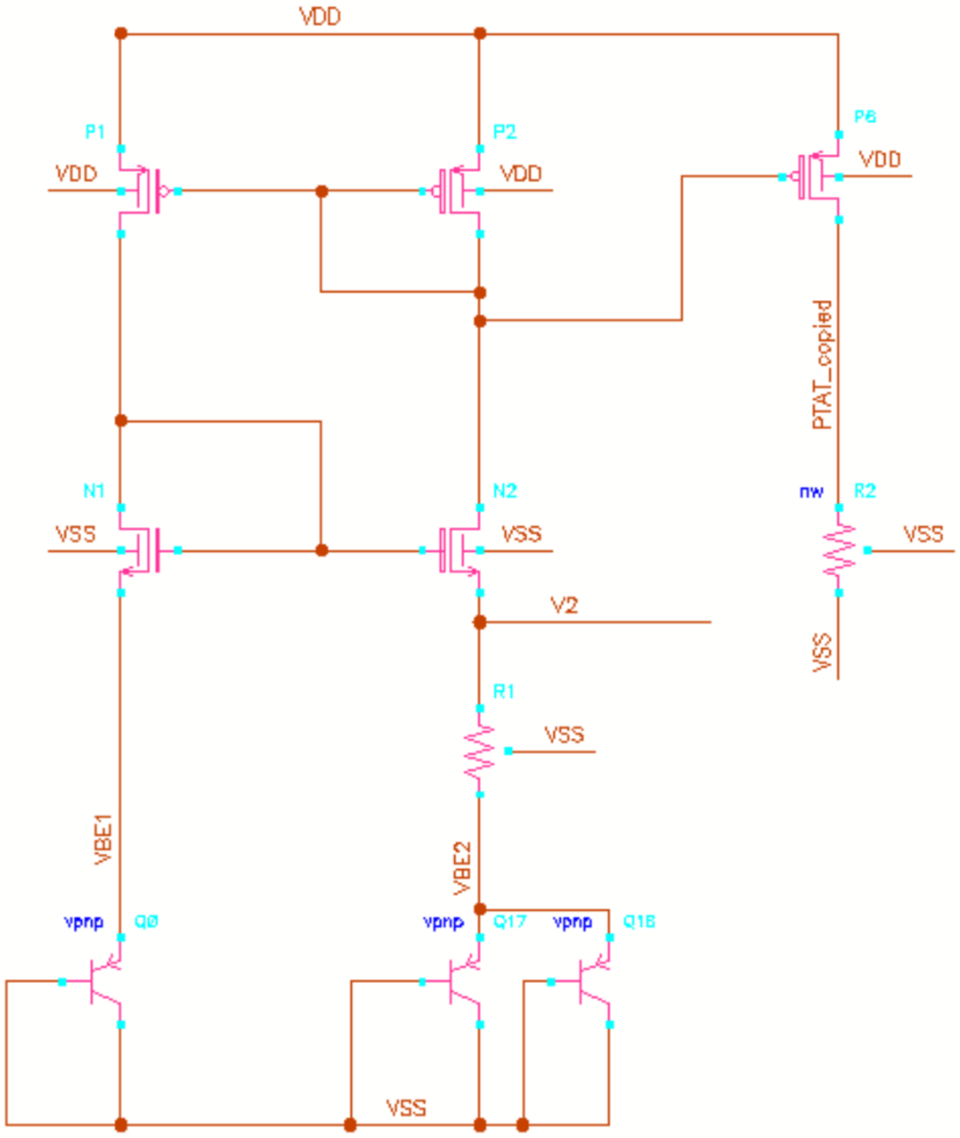
PTAP Current

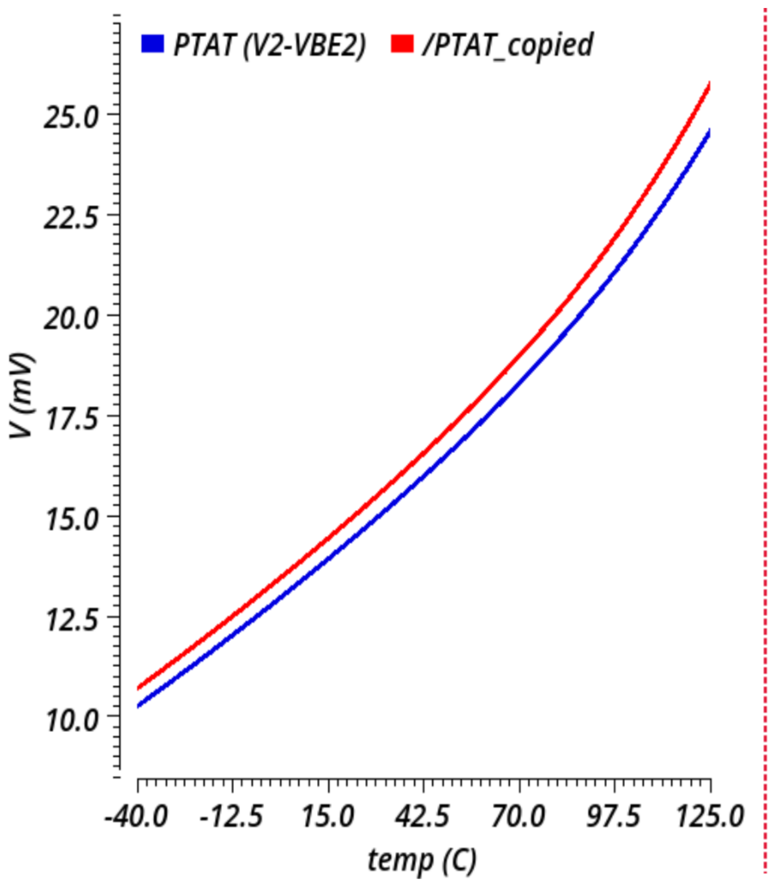
→ Use CM to copy PTAT current

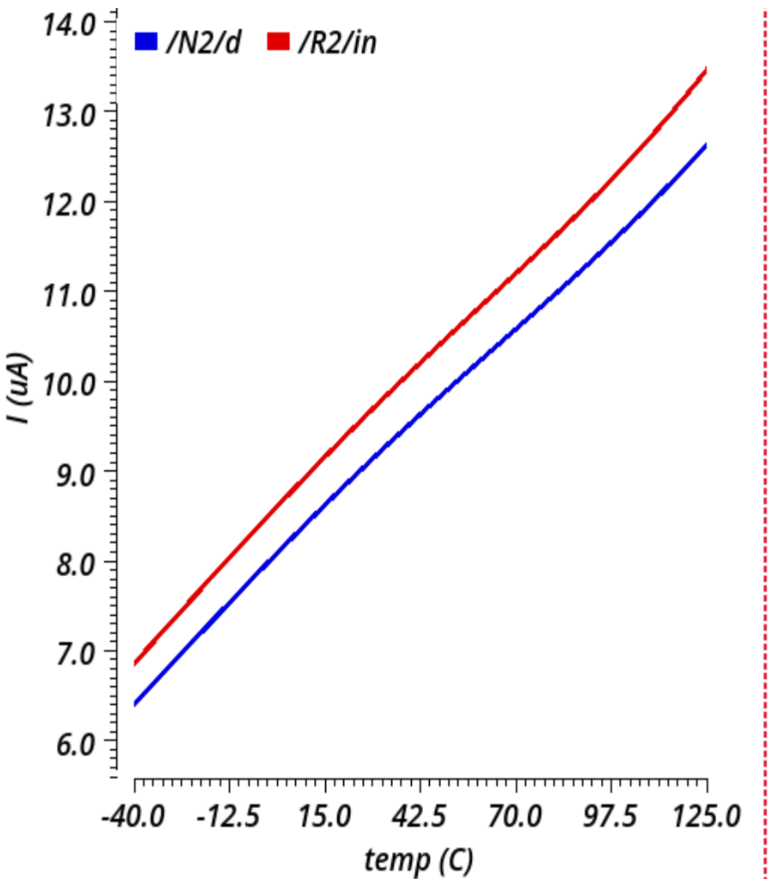
→ Drop it across a resistor to generate PTAT Voltage



Extracting PTAT Voltage Separately

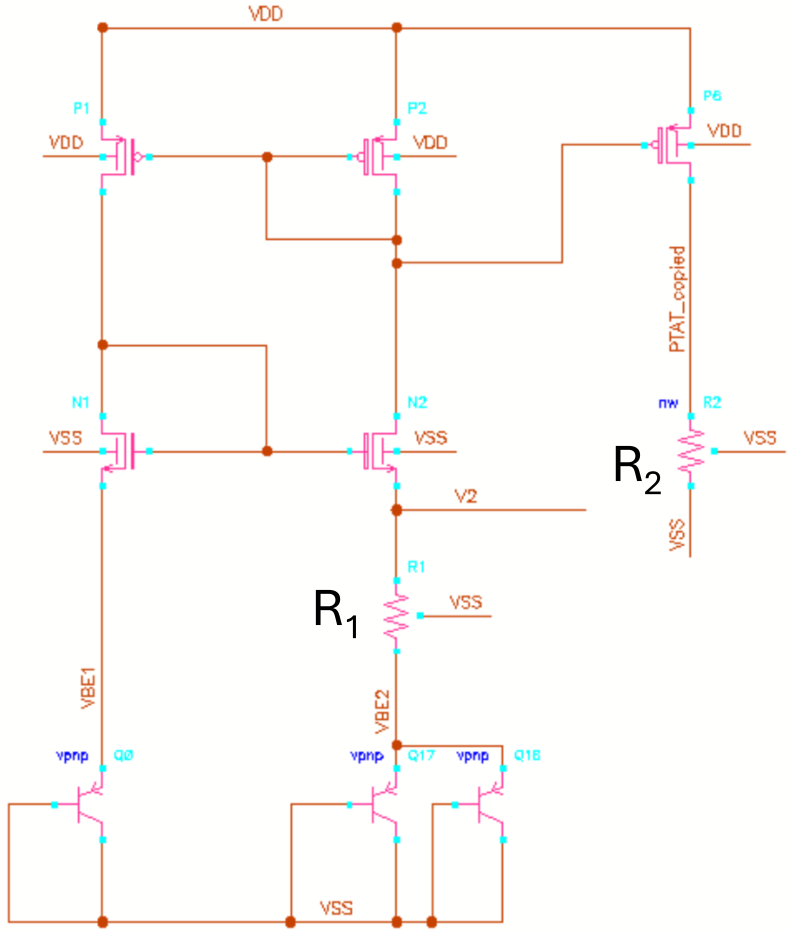






Review: Idea of BGR

$$V_{BE} = \underbrace{\frac{kT}{q}\ln(I_c)}_{\text{Weak PTAT}} \underbrace{- \frac{kT}{q}\ln(E) - \frac{5}{2}\frac{kT}{q}\ln(T)}_{\text{Strong CTAT}} + \underbrace{V_{BG}}_{\text{Constant BG voltage}}$$

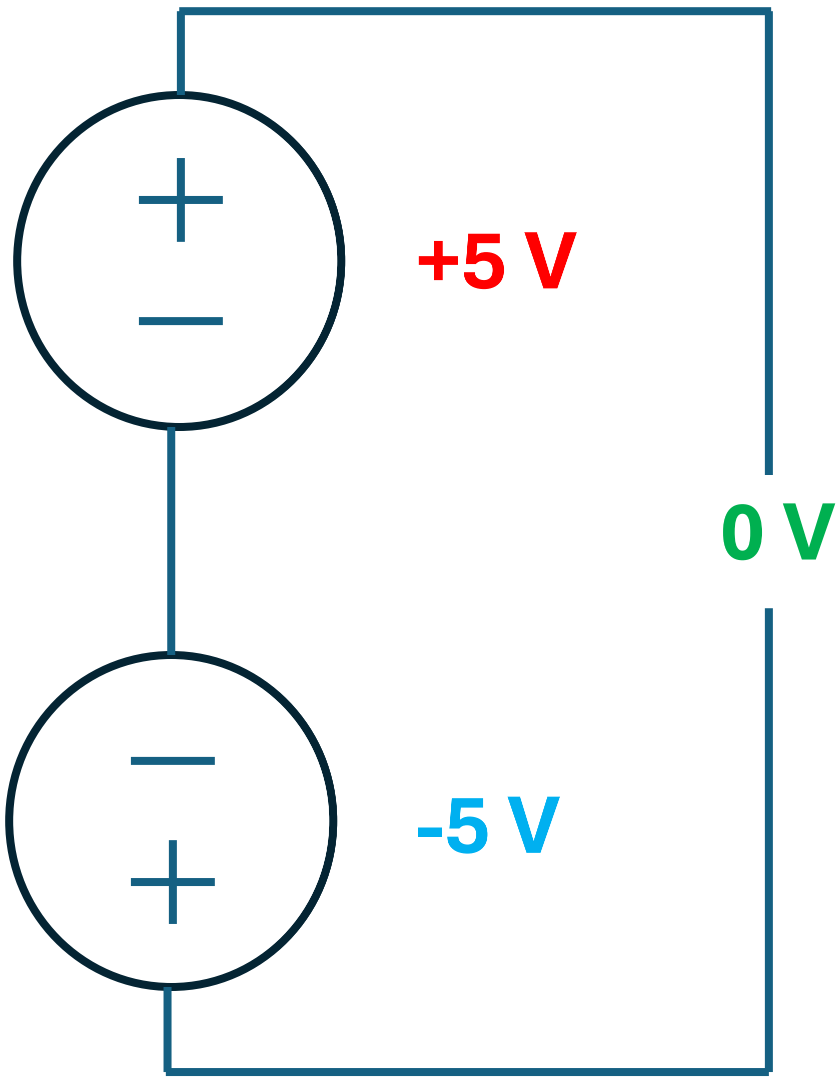


- Increase "Weak PTAT" to be equal to "Strong CTAT"
  - They will cancel each other!
  - Mathematically
    - ZTC (T) = K. PTAT (T) + CTAT (T)

$$= \frac{R_2}{R_1}.\ \text{PTAT (T)} + \text{CTAT (T)}$$

Increase R2/R1 Ratio to make PTAT Stronger

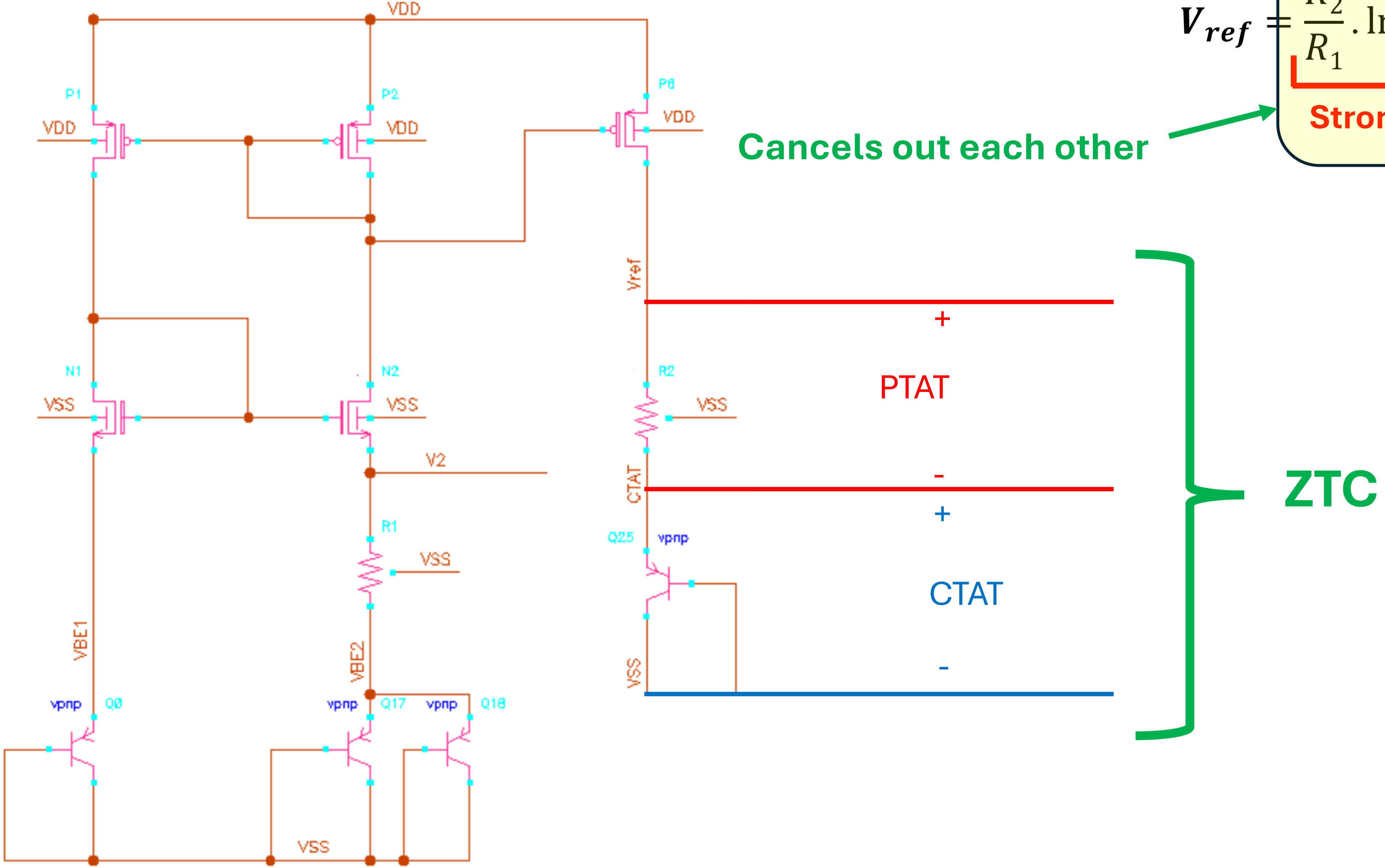
Review: Kirchhoff's Voltage Law (KVL)



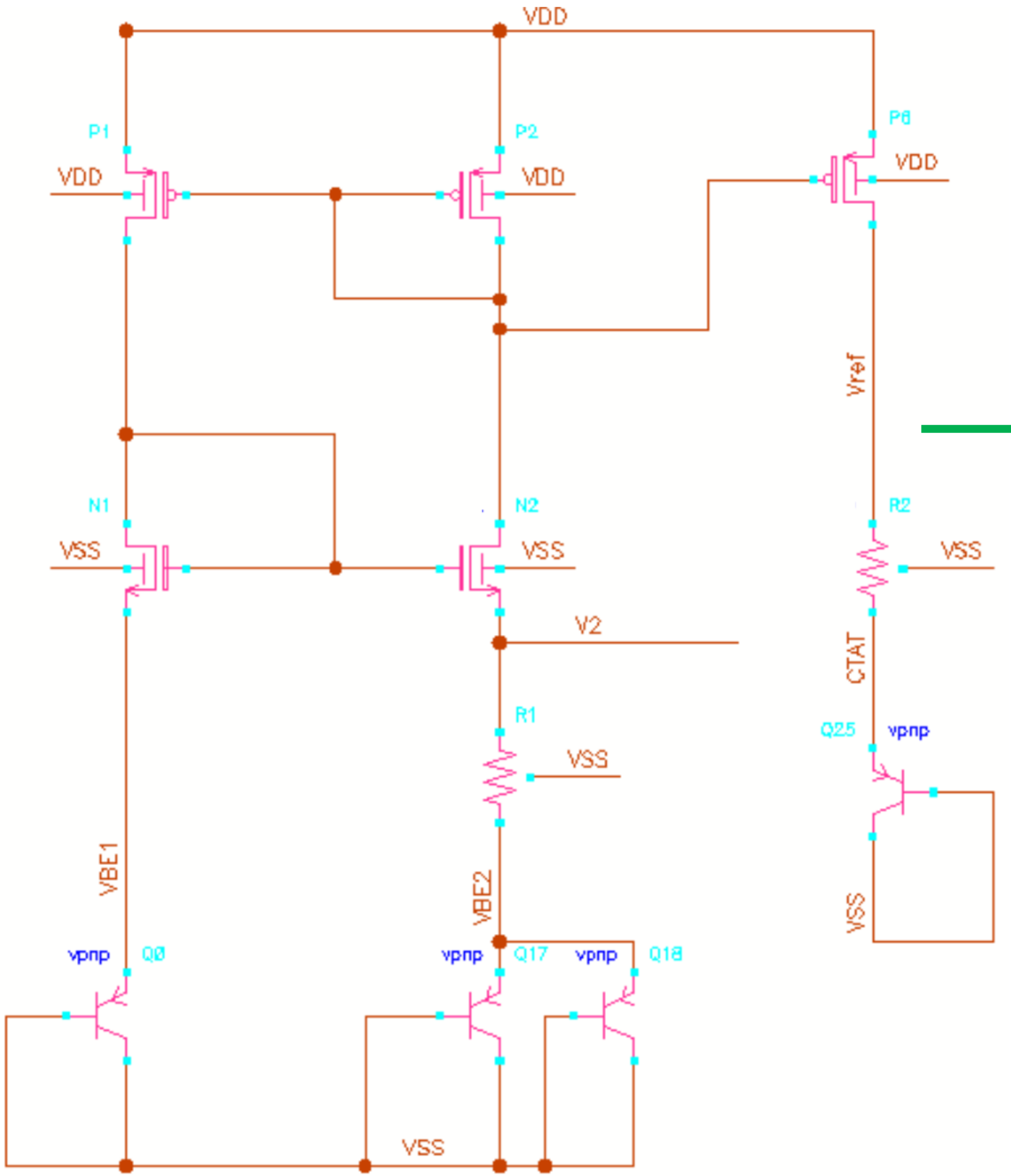
BGR: Apply KVL

$$\boldsymbol{V_{ref}} = \underbrace{\frac{R_2}{R_1}.\ln(I_c)\frac{kT}{q}}_{\text{Strong PTAT}} - \underbrace{\boldsymbol{V}_{\text{BE}}}_{\text{Strong CTAT}} + \underbrace{V_{BG}}_{\text{BG voltage}}$$

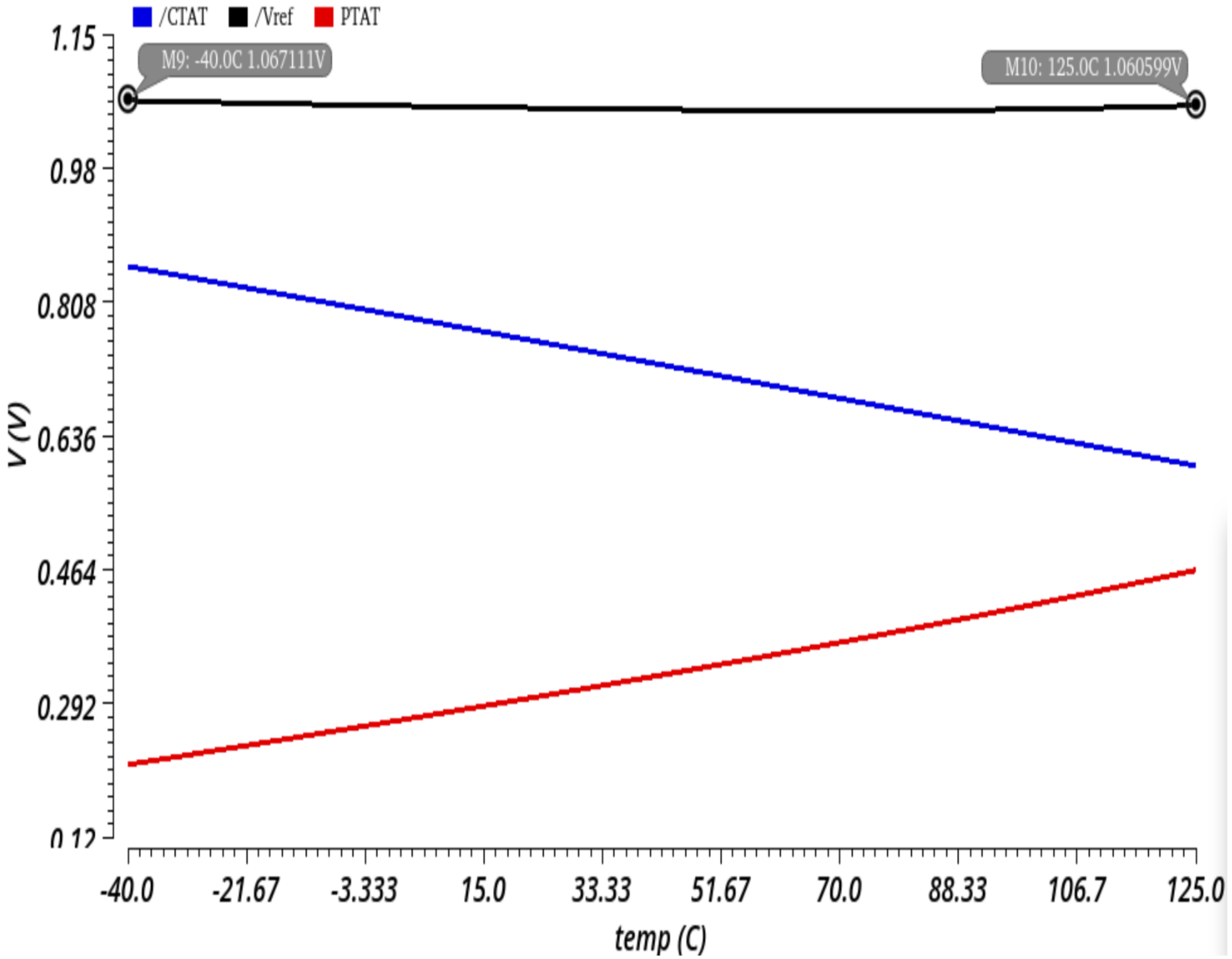
Cancels out each other



Simulation output of BGR



Sweep the temp from -40°C to 125°C



Temperature Coefficient

Vref_h = 1.061 V
Vref_l = 1.067 V
T_h = 125°C
T_l = -40°C
Vref@25C = 1.060 V

Temp Coefficient = $\frac{|Vref_h - Vref_l|}{T_h - T_l}\ x\ \frac{10^6}{Vref@25°C} = {}^{ppm}/_{°C}$

$$\frac{|1.061 - 1.067|}{125 - (-40)}\ x\ \frac{10^6}{1.060} = 34.3\ {}^{ppm}/_{°C}$$

The plotted derivative function is

$$\frac{\partial(voltage)}{\partial(temperature)}$$

in units of

$$\frac{V}{^\circ C}$$

. Divide this function by your nominal Vref - e.g. 1.22V @ 25°C - and multiply it by 1.000.000 (ppm = part per million), so you get

$$\frac{V}{^\circ C} \times \frac{10^6}{Vref[V])} = \frac{ppm}{^\circ C}$$

.

> kokykokykoky said:
>
> So which point should I take to be the TC?

The relative temperature dependence of your ref. voltage (in

$$\frac{ppm}{^\circ C}$$

) will change over the temperature range. Which value you should take depends on your specification needs: you could specify several

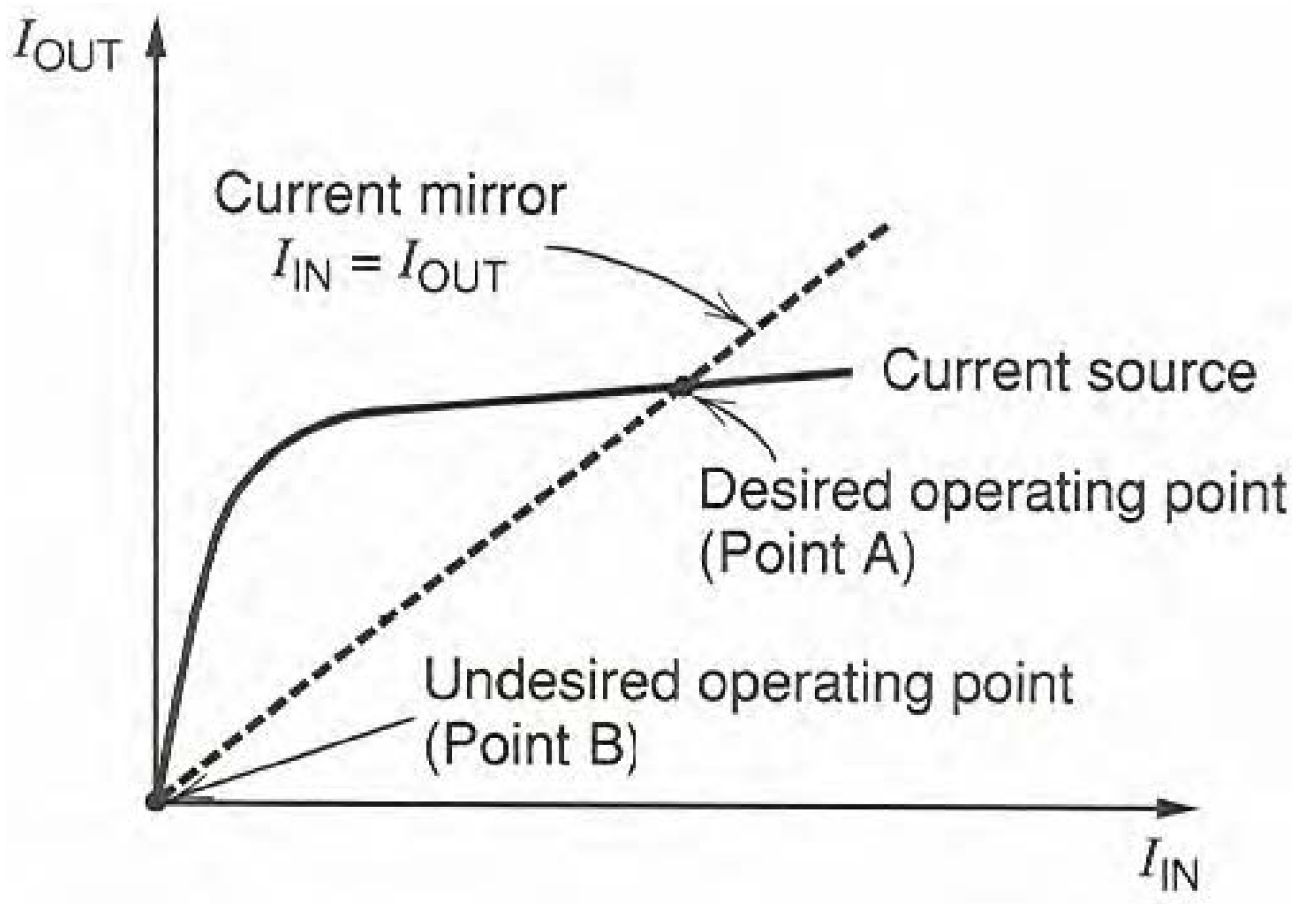
$$\frac{ppm}{^\circ C}$$

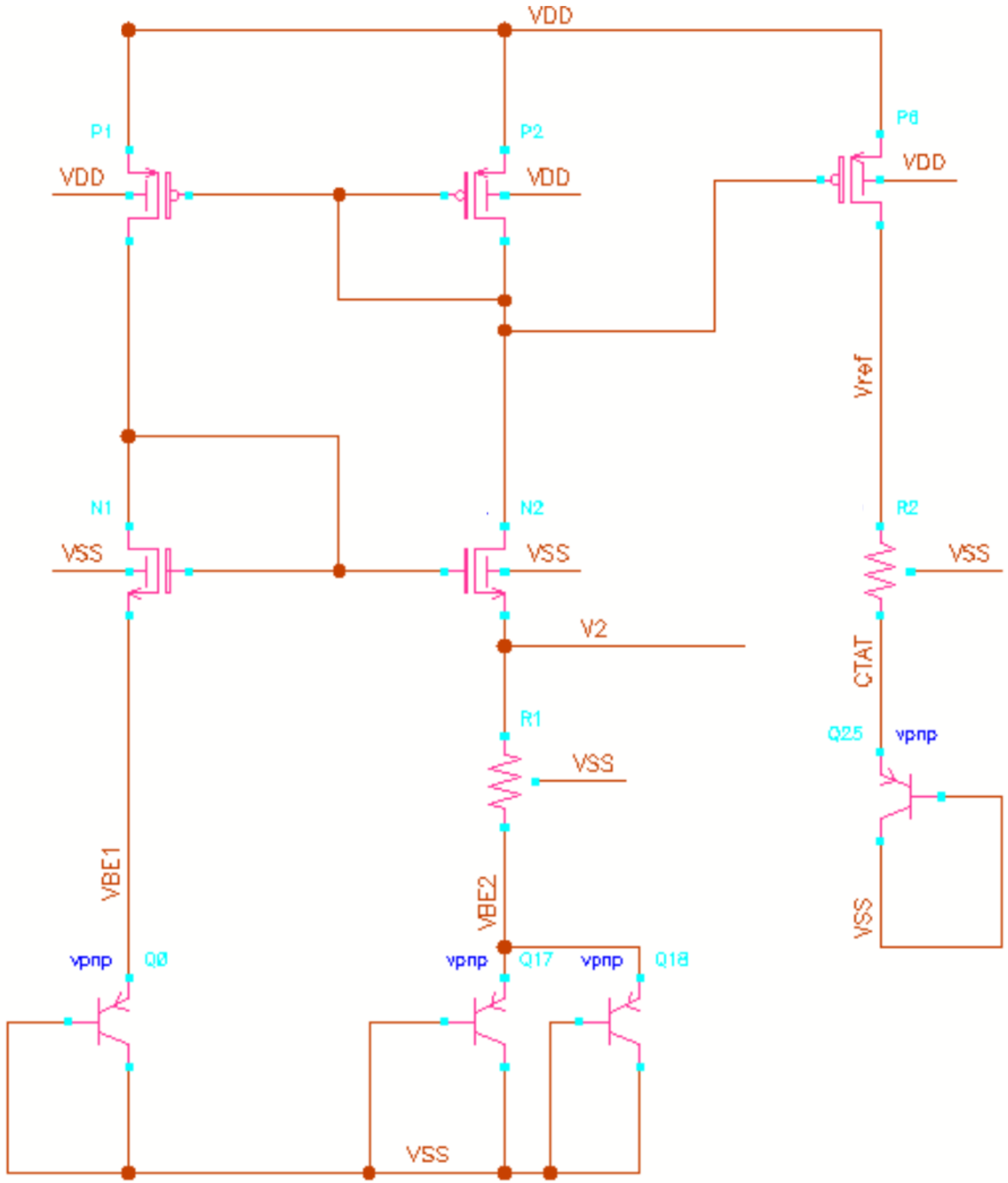
values for their corresponding temperature points, or you could specify min. & max values for a specified temperature range, or a mean value for such a range ± its max. deviations, e.g. for the application temperature range.

See also company bandGap dataSheets how they specify their values.

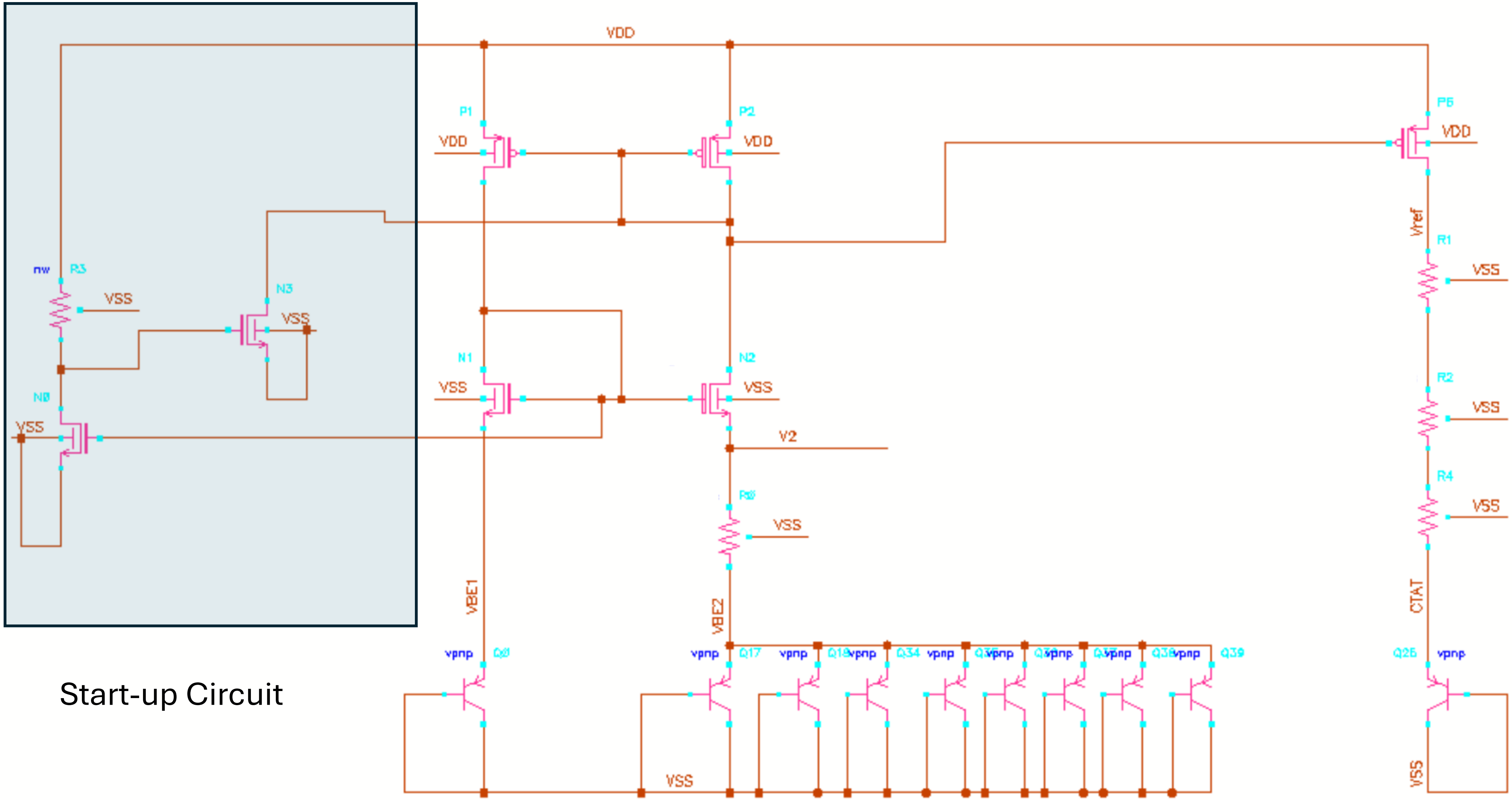
https://www.edaboard.com/threads/how-to-measure-tc-in-bandgap-using-cadence-simulation.27595/

Stable Biasing Point of a Reference Source





Start-up Circuit



Start-up Circuit

Some good sources for learning more!

- New Analog Circuit Design (By Prof. Ali Hajimiri, Caltech) Lectures 131N to 134N
- Design of Bandgap Reference

References

[1] P. E. Allen and D. R. Holberg, “CMOS Analog Circuit Design,” 2nd Edition, Oxford University Press, New York, 2004

[2] Shaheen, Amrozia, Wasif Zia, and Muhammad Sabieh Anwar. "Band structure and electrical conductivity in semiconductors." LUMS School of Science and Engineering, Lahore, Pakistan (2011).

[3] J. Baker, “Circuit Design, Layout and Simulation”, 4th Edition, John Wiley & Sons, July 2019. ISBN 9781119481515

Thank you!