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INTEGRATED ELECTRONICS

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Topics

1. Power Supplies
2. **Bias Circuits**
3. Operational Amplifiers
4. Applications of Operational Amplifiers

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Reference Textbooks

1. **Sedra and Smith, *Microelectronic Circuits*, 5th Edition, Oxford University Press, 2004.**
2. **Gray, Hurst, Lewis and Meyer, *Analysis and Design of Analogue Integrated Circuits*, 4th Edition, John Wiley & Sons, 2001.**
3. **Franco S, *Design with Operational Amplifiers and Analog Integrated Circuits*, 3rd Edition, McGraw-Hill, 2002.**

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Bias Circuits

1. Introduction
2. Current Mirrors
3. Bias circuits based on V_{BE} or V_{GS} of a transistor, Thermal voltage V_T, Breakdown voltage of a reverse-biased pn junction
4. Voltage Level Shifters

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Introduction

Bias Circuits should provide a *constant* bias current and/or voltage so that the circuit parameters do not change over varying supply voltages, temperature and other variations.

The Figure-of-Merit to qualify how well a desired parameter remains unchanged to the variation of a given parameter is Sensitivity.

The <u>Sensitivity</u> of a desired parameter (e.g. output current) to the variation of a given parameter (e.g. supply voltage) is:

$$S_{V_{CC}}^{I_O} = \frac{\Delta I_O / I_O}{\Delta V_{CC} / V_{CC}} = \frac{V_{CC}}{I_O}\frac{\partial I_O}{\partial V_{CC}}$$

In general, the sensitivity of currents or voltages in a bias circuit to the variation of other parameters should be kept small.

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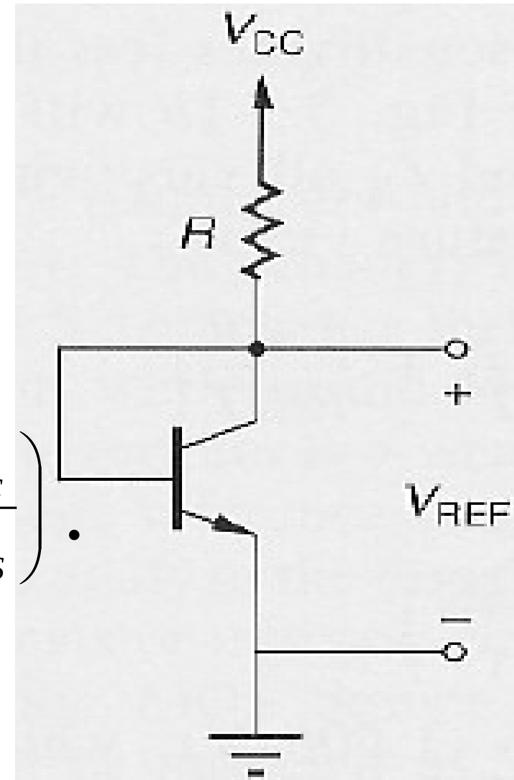
Introduction

Example 1: Determine the sensitivity of V_{REF} to V_{CC} for the circuit shown in right. Assume $V_{CC} >> V_{REF}$, V_{CC} = 5V, R = 43kΩ and I_S = 0.4fA.



Solution: Since $I_C = I_S \exp(V_{BE}/V_T)$,

$$V_{REF} = V_{BE} = V_T \ln(I_C / I_S) = V_T \ln\left(\frac{V_{CC} - V_{REF}}{RI_S}\right) \approx V_T \ln\left(\frac{V_{CC}}{RI_S}\right).$$

Hence $S_{V_{CC}}^{V_{REF}} = \frac{V_{CC}}{V_{REF}} \frac{\partial V_{REF}}{\partial V_{CC}} \cong \frac{1}{\ln(V_{CC}/RI_S)} \cong 0.0379.$

If V_{CC} changes by 10%, V_{REF} will change by 0.379%, which is large for a voltage bias circuit.

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Introduction

The Fractional Temperature Coefficient of a desired parameter (e.g. output current) is the fractional variation of the desired parameter to the variation of temperature. Denoted as TC_F, it is defined as:

$$TC_F = \frac{1}{I_O}\frac{\partial I_O}{\partial T}$$

Here the TC_F of an output current is used, other parameters can similarly be qualified.

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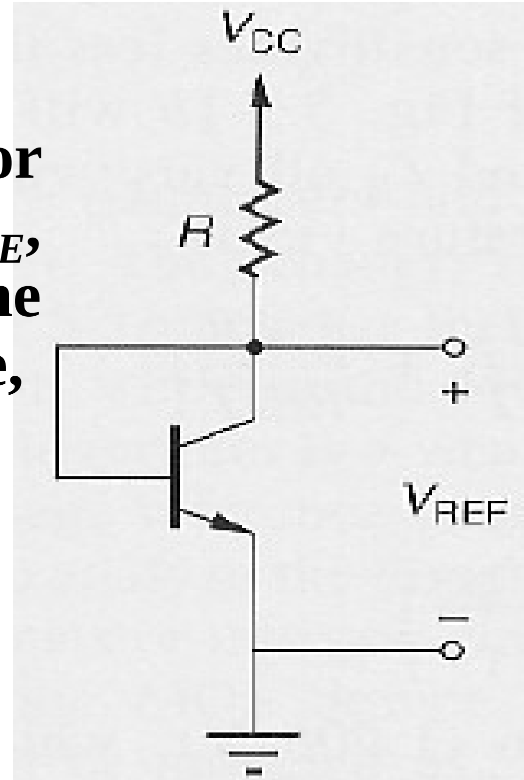
Introduction



Example 2: Determine the $TC_F(V_{REF})$ for V_{CC} for the circuit shown. Assume $V_{CC} >> V_{BE}$, $I_S = KT^3 \exp(-V_{GO}/V_T)$ where V_{GO} = 1.205V is the bandgap of silicon and is independent of temperature, $TC_F(R)$=1500ppm/°C, V_{REF} =0.7V, and T=300°K.

Solution:

$$V_{REF} \approx V_T \ln\left(\frac{V_{CC}}{RI_S}\right)$$

where

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

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Introduction

$$\frac{\partial V_{REF}}{\partial T} = \frac{\partial V_T}{\partial T}\ln\frac{V_{CC}}{RI_S} + V_T\frac{\partial}{\partial T}(\ln\frac{V_{CC}}{RI_S}) = \frac{k}{q}\ln\frac{V_{CC}}{RI_S} + V_T\frac{\partial}{\partial T}(\ln\frac{V_{CC}}{RI_S})$$

$$= \frac{kT}{qT}\ln\frac{V_{CC}}{RI_S} + V_T\frac{\partial}{\partial T}(\ln\frac{V_{CC}}{RI_S}) = \frac{V_{REF}}{T} + V_T\frac{\partial}{\partial T}(\ln\frac{V_{CC}}{RI_S})$$

$$= \frac{V_{REF}}{T} + V_T\frac{RI_S}{V_{CC}}\frac{\partial}{\partial T}(\frac{V_{CC}}{RI_S}) = \frac{V_{REF}}{T} + V_T\frac{RI_S}{V_{CC}}[\frac{RI_S\cdot 0 - V_{CC}\cdot\frac{\partial}{\partial T}(RI_S)}{(RI_S)^2}]$$

$$= \frac{V_{REF}}{T} - \frac{V_T}{RI_S}\frac{\partial}{\partial T}(RI_S) = \frac{V_{REF}}{T} - \frac{V_T}{RI_S}[I_S\frac{\partial R}{\partial T} + R\frac{\partial I_S}{\partial T}]$$

$$= \frac{V_{REF}}{T} - V_T\left(\frac{1}{R}\frac{\partial R}{\partial T} + \frac{1}{I_S}\frac{\partial I_S}{\partial T}\right).$$

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Introduction

Since $I_S = kT^3 \exp(-V_{GO}/V_T)$ **, we can get**

$$\frac{\partial I_S}{\partial T} = 3kT^2 \exp(-\frac{V_{GO}}{V_T}) + kT^3 \frac{\partial}{\partial T}[\exp(-\frac{V_{GO}}{V_T})]$$

$$= \frac{3I_S}{T} + kT^3 \exp(-\frac{V_{GO}}{V_T}) \frac{\partial}{\partial T}(-\frac{V_{GO}}{V_T}) = \frac{3I_S}{T} - I_S \frac{\partial}{\partial T}(\frac{V_{GO}}{V_T})$$

$$= \frac{3I_S}{T} - I_S(\frac{V_T \cdot 0 - V_{GO}\frac{\partial V_T}{\partial T}}{V_T^2}) = \frac{3I_S}{T} + I_S(\frac{V_{GO}\frac{k}{q}}{V_T^2}) = \frac{3I_S}{T} + \frac{I_S}{T}\frac{V_{GO}}{V_T} \quad .$$

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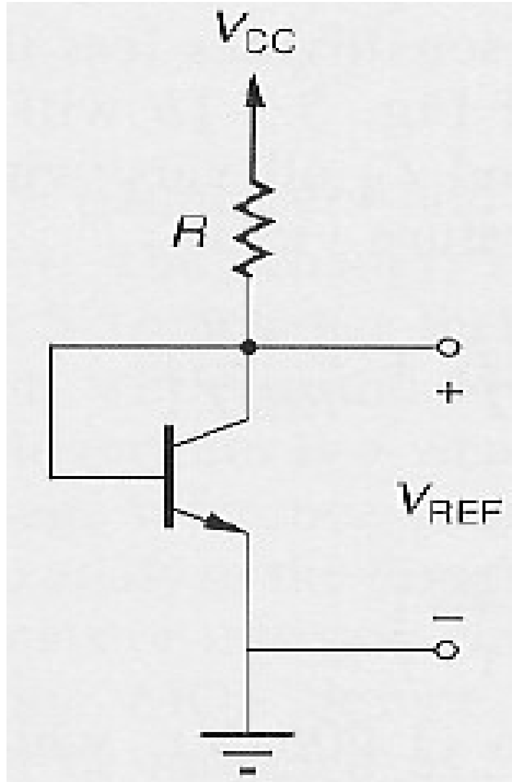
Introduction

$$\frac{\partial V_{REF}}{\partial T}=\frac{V_{REF}}{T}-V_T\left(\frac{1}{I_S}\frac{\partial I_S}{\partial T}+\frac{1}{R}\frac{\partial R}{\partial T}\right)=\frac{V_{REF}}{T}-V_T\left(\frac{1}{I_S}\left(\frac{3I_S}{T}+\frac{I_S}{T}\frac{V_{GO}}{V_T}\right)+\frac{1}{R}\frac{\partial R}{\partial T}\right)$$

$$=\frac{V_{REF}}{T}-V_T\left(\frac{3}{T}+\frac{V_{GO}}{TV_T}+\frac{1}{R}\frac{\partial R}{\partial T}\right)=\frac{V_{REF}}{T}-\left(\frac{3V_T}{T}+\frac{V_{GO}}{T}+\frac{V_T}{R}\frac{\partial R}{\partial T}\right).$$



$$TC_F(V_{REF})=\frac{1}{V_{REF}}\frac{\partial V_{REF}}{\partial T}$$

$$=\frac{V_{REF}-3V_T-V_{GO}}{V_{REF}T}-\frac{V_T}{V_{REF}}\frac{1}{R}\frac{\partial R}{\partial T}$$

$$=\frac{700-78-1205}{700\cdot 300}-\frac{26}{700}1500\approx -2832\,ppm/^{\circ}C\quad.$$

This voltage bias circuit has a large temperature coefficient.

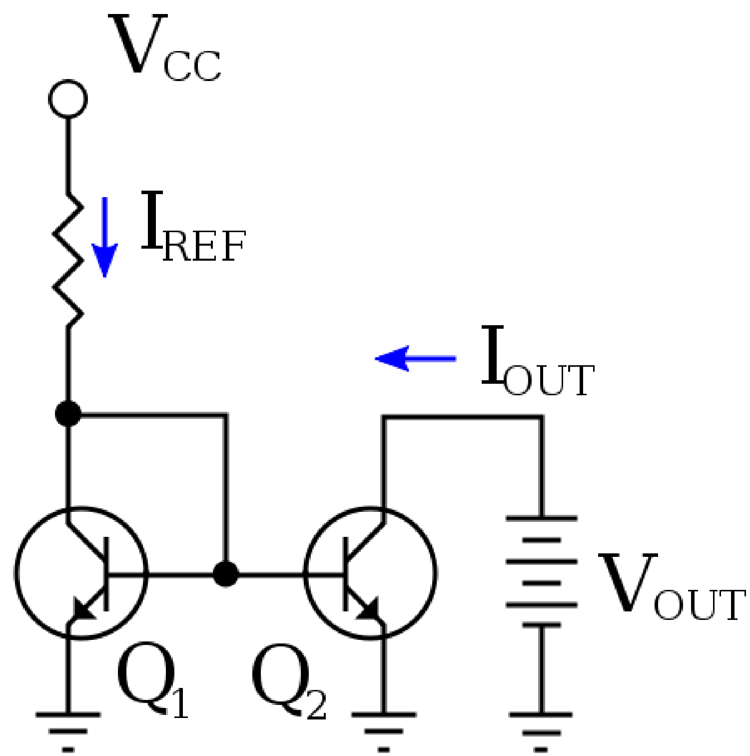
Current Mirrors

For BJT in active mode,

$$I_{C1} = I_{S1} \exp\left(\frac{V_{BE1}}{V_T}\right) \Rightarrow V_{BE1} = V_T \ln\left(\frac{I_{C1}}{I_{S1}}\right) .$$

Since V_{BE1}=V_{BE2}, So $$\frac{I_{C1}}{I_{C2}} = \frac{I_{S1}}{I_{S2}} .$$

As $I_S \propto$ emitter area, the ratio of the emitter areas to a first order determines the current ratio of the collectors.



Basic BJT current mirror

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Current Mirrors

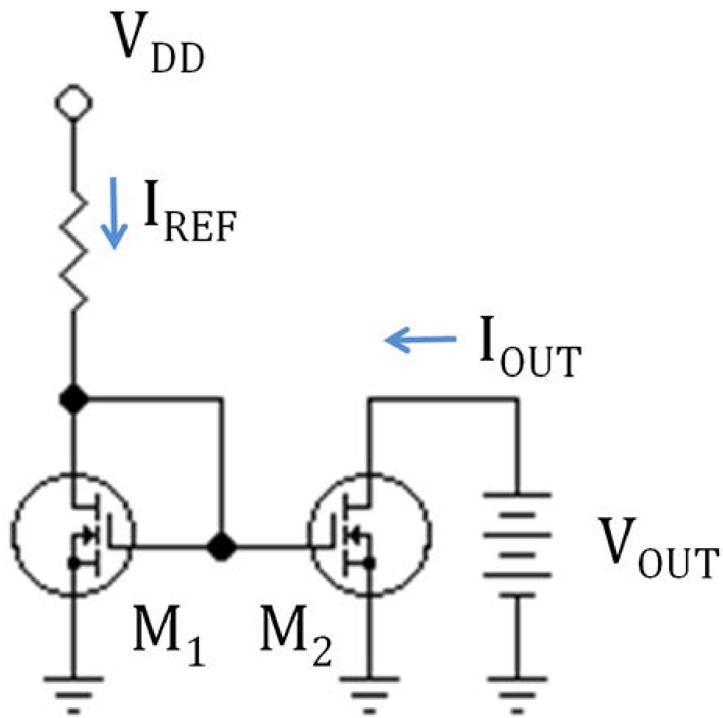
For CMOS in saturation mode,

$$I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}(V_{GS} - V_t)^2 .$$

Since $V_{GS1}=V_{GS2}$,

$$\frac{I_{D1}}{I_{D2}} = \frac{(W/L)_1}{(W/L)_2} .$$

The ratio of the (W/L) or aspect ratio of the CMOS transistors to a first order determines the drain current ratio.



Basic MOS current mirror

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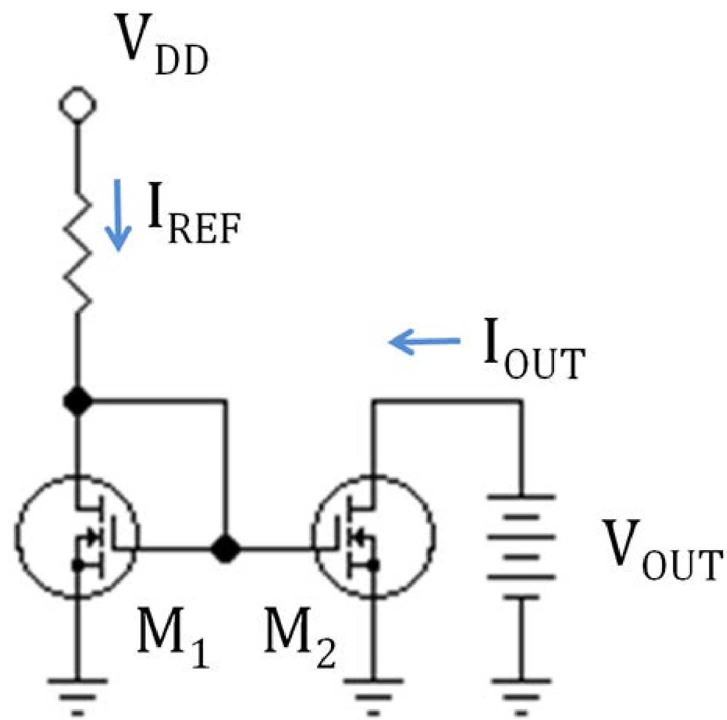
Current Mirrors

Example 3: Given two MOSFETs of channe lengths of 10 µm, channel widths of 100 µm threshold voltage of 1 V, early voltage of 100 V and $\mu_n C_{ox}$ = 20mA/V^2, it is required t design the circuit for a basic MOSFET constant current source to obtain an outpu of 100 µA with a power supply V_{DD} = 5 V. What is the lowest possible value of output voltage? Find the change in output current resulting from a 3-V change in output voltage.



Basic MOS current mirror

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Current Mirrors

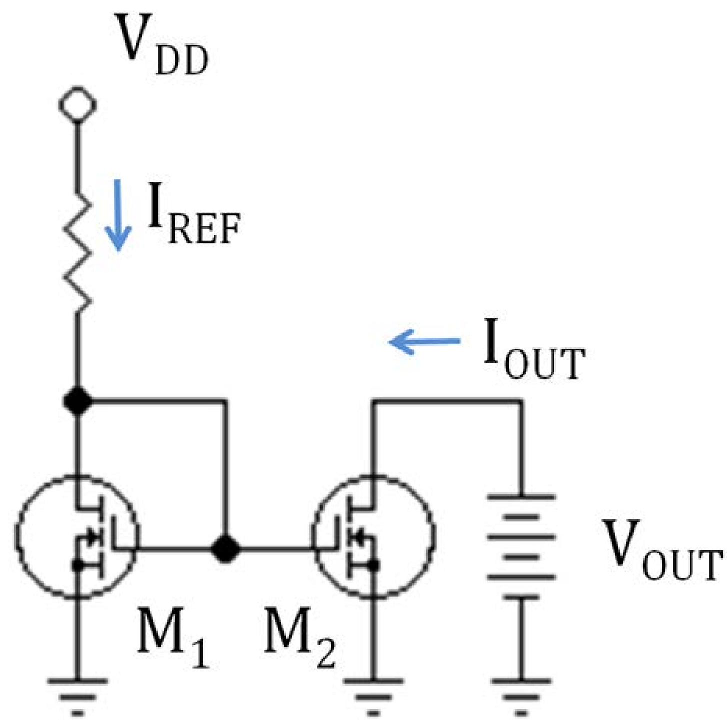
Solution: $I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}(V_{GS}-V_t)^2(1+\frac{V_{DS}}{V_A})$.

$$100\times10^{-6} = \frac{20\times10^{-3}}{2}\frac{100}{10}(V_{GS}-1)^2(1+\frac{V_{GS}}{100})$$

$$\approx \frac{20\times10^{-3}}{2}\frac{100}{10}(V_{GS}-1)^2 .$$

$V_{GS} \approx 1.03$ V .

$$R = \frac{V_{DD}-V_{GS}}{I_o} \approx \frac{5-1.03}{0.0001} = 39.7 \quad k\Omega \ .$$



Basic MOS current mirror

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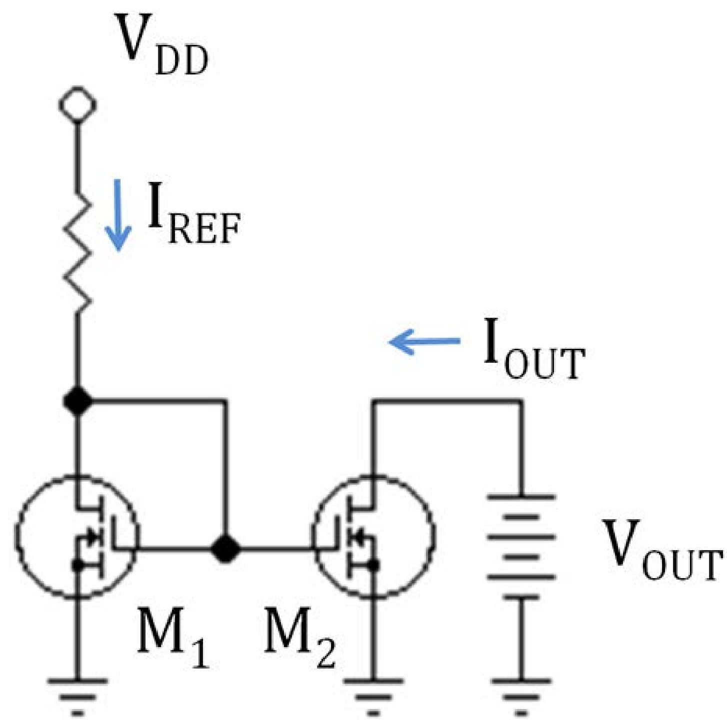
Current Mirrors

Solution: $V_o = V_{DS2} \geq V_{GS2} - V_t$.

$$V_{o\min} = V_{DS2} = V_{GS2} - V_t = V_{GS1} - V_t \approx 1.03 - 1 = 0.03 \quad V .$$

$$r_o = \frac{V_A}{I_o} = \frac{100}{0.0001} = 1 \quad M\Omega .$$

$$\Delta I_o = \frac{\Delta V_o}{r_o} = 3 \quad \mu A .$$



Basic MOS current mirror

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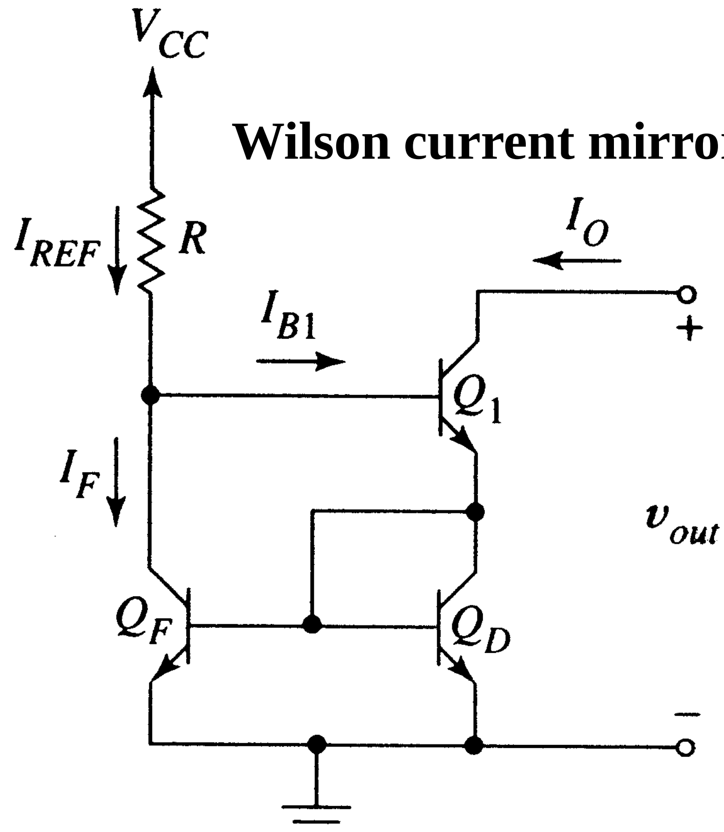
Current Mirrors

The Wilson current mirror has the advantage of virtually eliminating the base current mis-match of the basic current mirror thereby ensuring that the output current I_O is almost equal to the reference or input current I_{REF}. It also has a very high output impedance.

$$\frac{I_o}{I_{REF}} = \frac{\beta^2 + 2\beta}{\beta^2 + 2\beta + 2} \ .$$

Wilson current mirror



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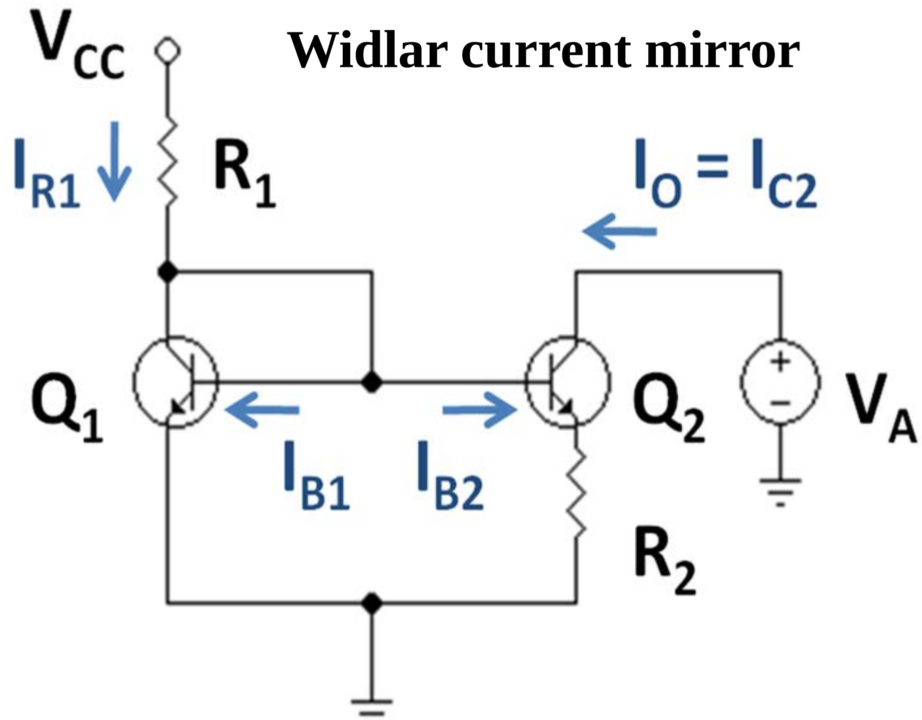
Current Mirrors

Widlar current mirror uses bipolar transistors, where the emitter resistor R_2 is connected to the output transistor Q_2, and has the effect of reducing the current in Q_2 relative to Q_1. The key to this circuit is that the voltage drop across the resistor R_2 subtracts from the base-emitter voltage of transistor Q_2, thereby turning this transistor off compared to transistor Q_1.

Widlar current mirror



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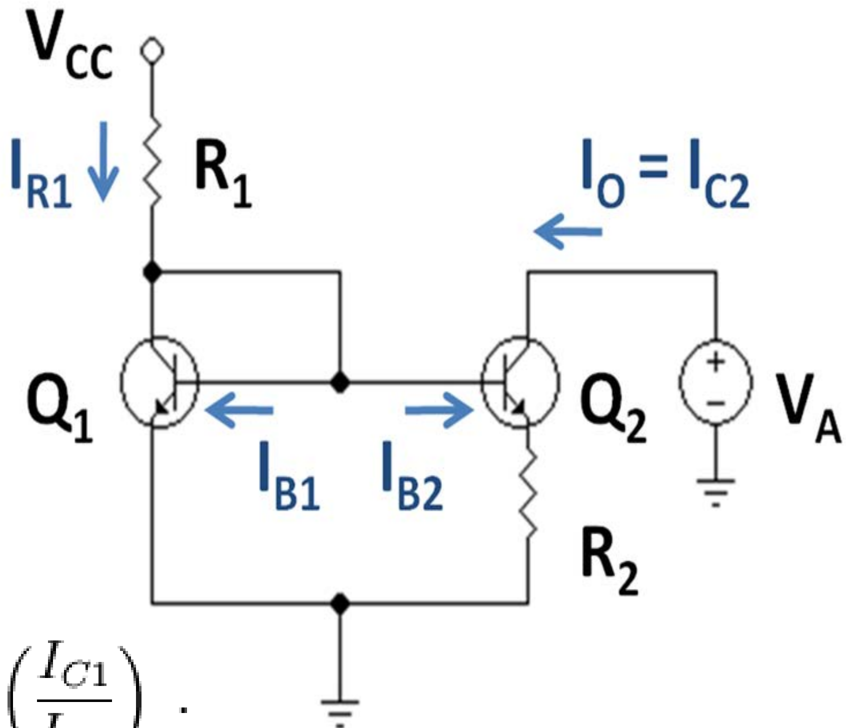
Current Mirrors

Example 4: Design a Widlar current mirror.



Select the desired output current I_O.

Select the reference current I_{R1}.

Find the collector current of Q_1

$$I_{C1} = \frac{\beta_1}{\beta_1 + 1}\left(I_{R1} - I_{C2}/\beta_2\right) .$$

Find the base voltage of Q_1

$$V_{BE1} = V_T \ln\left(\frac{I_{C1}}{I_S}\right) = V_A .$$

Find $R_1 = \dfrac{V_{CC} - V_A}{I_{R1}}$ **and** $R_2 = \dfrac{V_T}{(1 + 1/\beta_2)\, I_{C2}} \ln\left(\dfrac{I_{C1}}{I_{C2}}\right) .$

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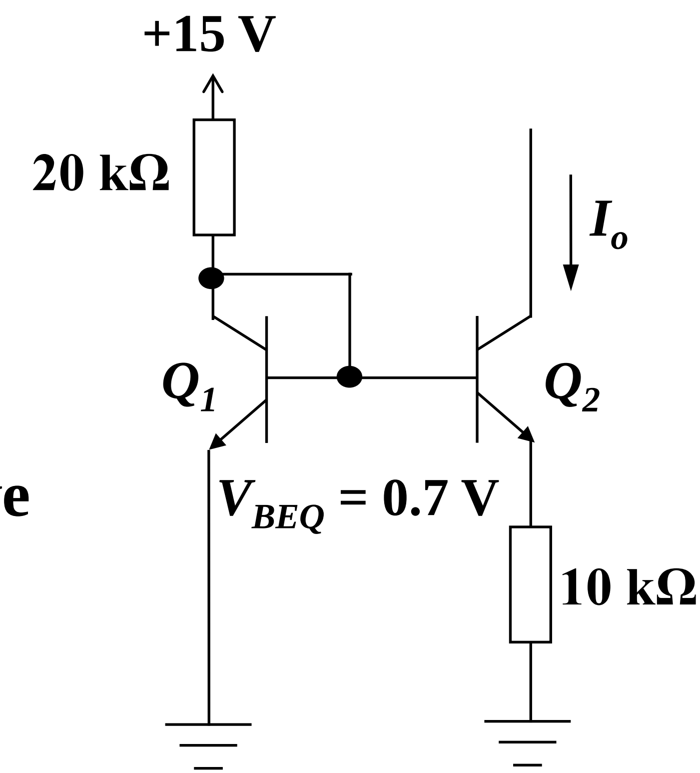
Current Mirrors

Example 5: For the Widlar current source given, assuming that the two transistors are identical, the early voltage is infinite, and the base currents are negligible, determine the output current and the sensitivity of the output current to the power–supply voltage.



Solution: Based on the given assumptions, we have

$$V_{BE1} - V_{BE2} - I_o R_2 = 0 \ .$$

$$V_T \ln\frac{I_{C1}}{I_{S1}} - V_T \ln\frac{I_{C2}}{I_{S2}} - I_o R_2 = 0 \ .$$

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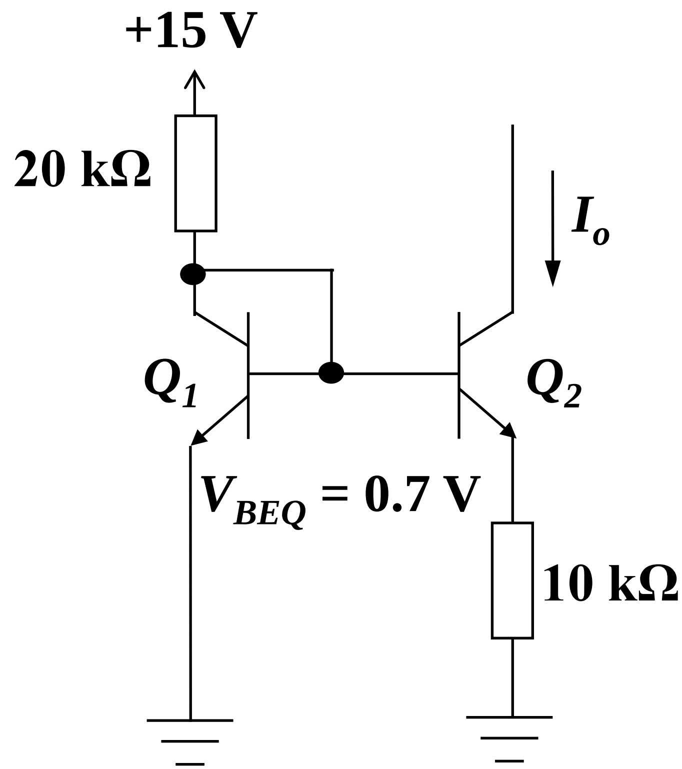
Current Mirrors

$$I_o R_2 = V_T \ln\frac{I_{C1}}{I_{C2}} = V_T \ln\frac{I_{C1}}{I_o} \quad .$$

$$I_{C1} = \frac{V_{CC} - V_{BEQ}}{R_1} = \frac{15-0.7}{20} = 0.715mA \quad .$$

$$I_o \times 10000 = 0.026\ln\frac{0.000715}{I_o} \quad .$$

$$I_o \approx 11\mu A \quad .$$



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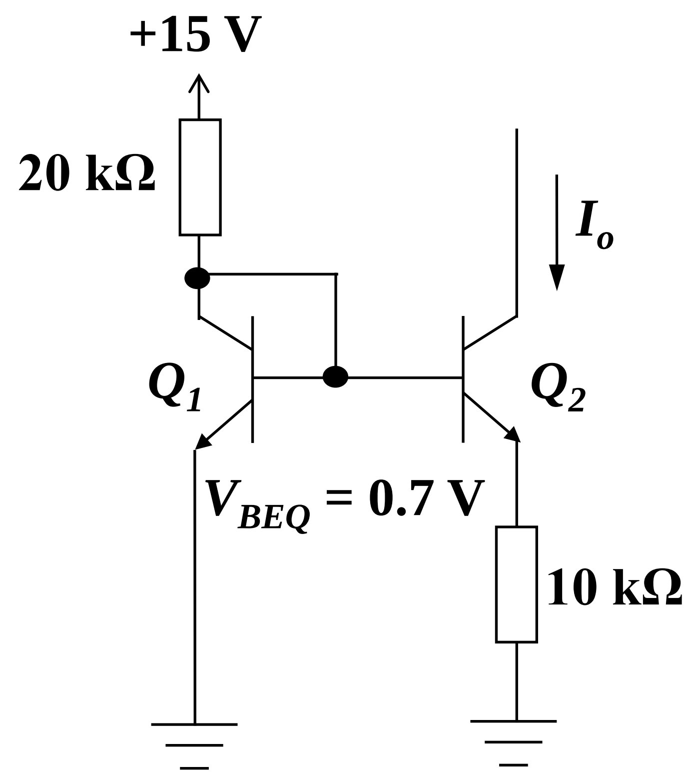
Current Mirrors

$$I_o R_2 = V_T \ln \frac{I_{C1}}{I_o} \quad .$$

Differentiating the above equation, we have:



$$R_2 \frac{\partial I_o}{\partial V_{CC}} = V_T \frac{\partial}{\partial V_{CC}} (\ln \frac{I_{C1}}{I_o})$$

$$= V_T \frac{I_o}{I_{C1}} [\frac{I_o \frac{\partial I_{C1}}{\partial V_{CC}} - I_{C1} \frac{\partial I_o}{\partial V_{CC}}}{I_o^2}] \quad .$$

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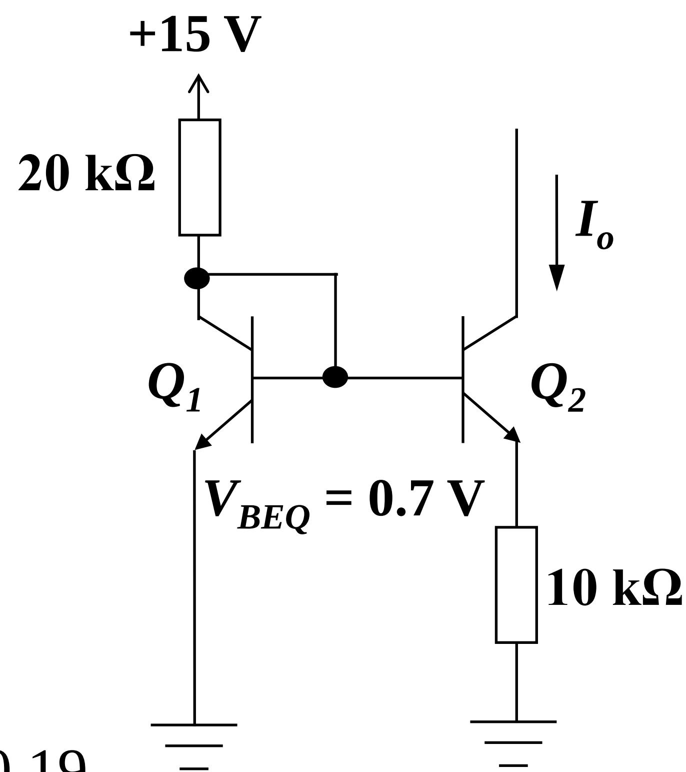
Current Mirrors

$$\frac{\partial I_o}{\partial V_{CC}} = \frac{I_o}{I_{C1}}\left(\frac{\frac{\partial I_{C1}}{\partial V_{CC}}}{1+\frac{I_o R_2}{V_T}}\right).$$

$$S_{V_{CC}}^{I_o} = \frac{V_{CC}}{I_o}\frac{\partial I_o}{\partial V_{CC}} = \frac{V_{CC}}{I_{C1}}\left(\frac{\frac{\partial I_{C1}}{\partial V_{CC}}}{1+\frac{I_o R_2}{V_T}}\right) = \frac{S_{V_{CC}}^{I_{C1}}}{1+\frac{I_o R_2}{V_T}}.$$

$$I_{C1} \approx \frac{V_{CC}}{R_1},\ S_{V_{CC}}^{I_{C1}} \approx 1,\quad S_{V_{CC}}^{I_o} = \frac{1}{1+\frac{I_o R_2}{V_T}} = \frac{1}{1+\frac{110}{26}} \approx 0.19.$$



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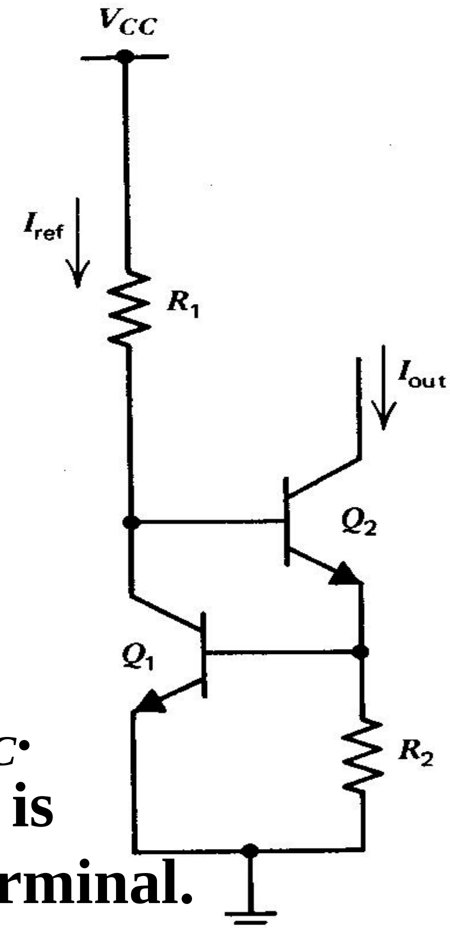
V_{BE}-Based Bias Circuit



I_{ref} is forced through Q_1, so Q_2 must supply enough current into R_2 so that V_{BEQ1}=V_{R2}.

Neglecting base currents we have I_{out}=I_{EQ2}=I_{R2}.

Hence we have

$$I_{out} = \frac{V_{BE1}}{R_2} = \frac{V_T}{R_2}\ln\left(\frac{I_{ref}}{I_{S1}}\right).$$

This bias circuit is NOT supply independent since V_{BEQ1} will change slightly with the supply voltage because I_{CQ1} is approximately proportional to V_{CC}. This is often a problem for bias circuits whose I_{out} is derived from a resistor connected to the supply terminal.

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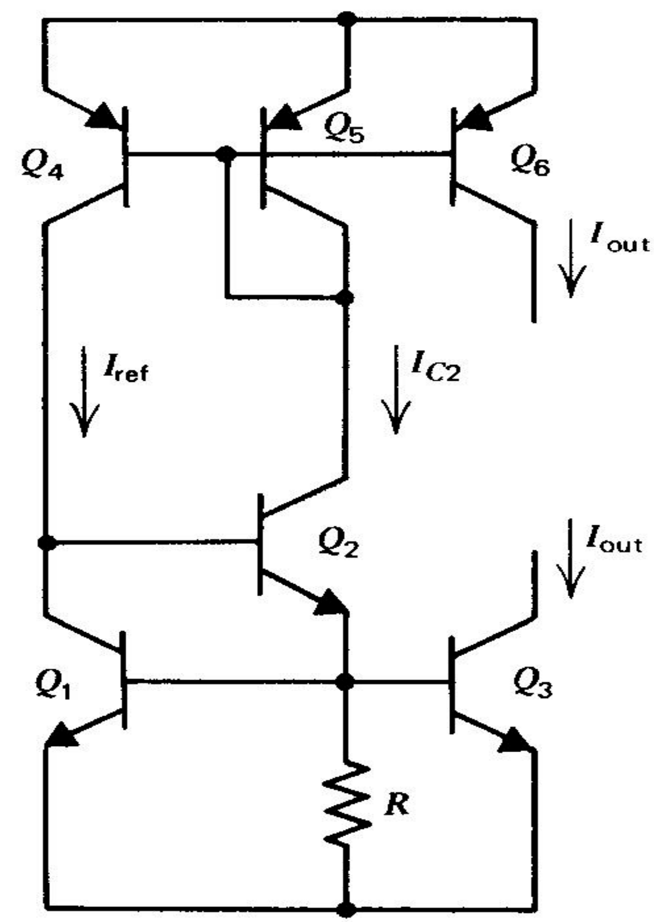
V_{BE}-Based Bias Circuit with Bootstrap

The idea is instead of developing the reference current through a resistor, the reference circuit is made to depend on the current source itself.

Assuming $V_A=\infty$ and neglecting base currents: Q_1, Q_2 and R are same as before.

Q_3 is the current mirror of Q_1.

Q_4, Q_5 and Q_6 are part of a simple current mirror, hence $I_{ref} = I_{C2}$.



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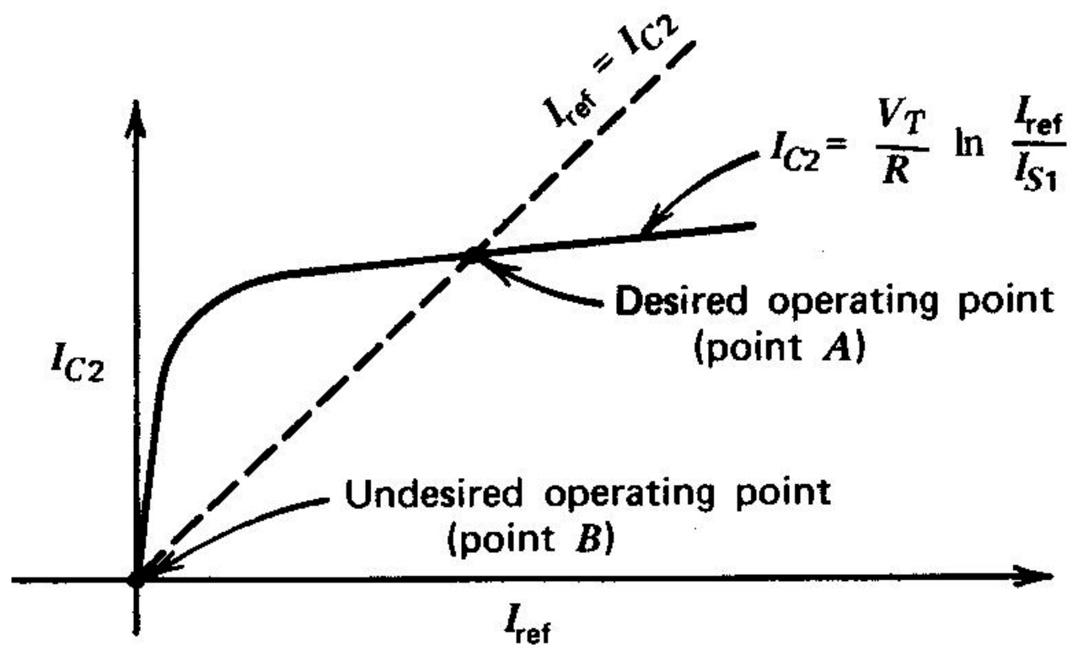
V_{BE}-Based Bias Circuit with Bootstrap

The operating point must satisfy both the upper current mirror and lower bias reference circuit.

The desired operating point is point A as shown in the figure. Need a start-up circuit to push the circuit out of the other possible operating point B. Here I_{out} is independent of the supply voltage.



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V_{BE}-Based Bias Circuit with Bootstrap

However, the TC_F of this circuit is an issue.

Since $I_{out} = \dfrac{V_{BE1}}{R}$,

$$\frac{\partial I_{out}}{\partial T} = \frac{1}{R}\frac{\partial V_{BE1}}{\partial T} - \frac{V_{BE1}}{R^2}\frac{\partial R}{\partial T} = I_{out}\left(\frac{1}{V_{BE1}}\frac{\partial V_{BE1}}{\partial T} - \frac{1}{R}\frac{\partial R}{\partial T}\right).$$

Hence $TC_F = \dfrac{1}{V_{BE1}}\dfrac{\partial V_{BE1}}{\partial T} - \dfrac{1}{R}\dfrac{\partial R}{\partial T}$.

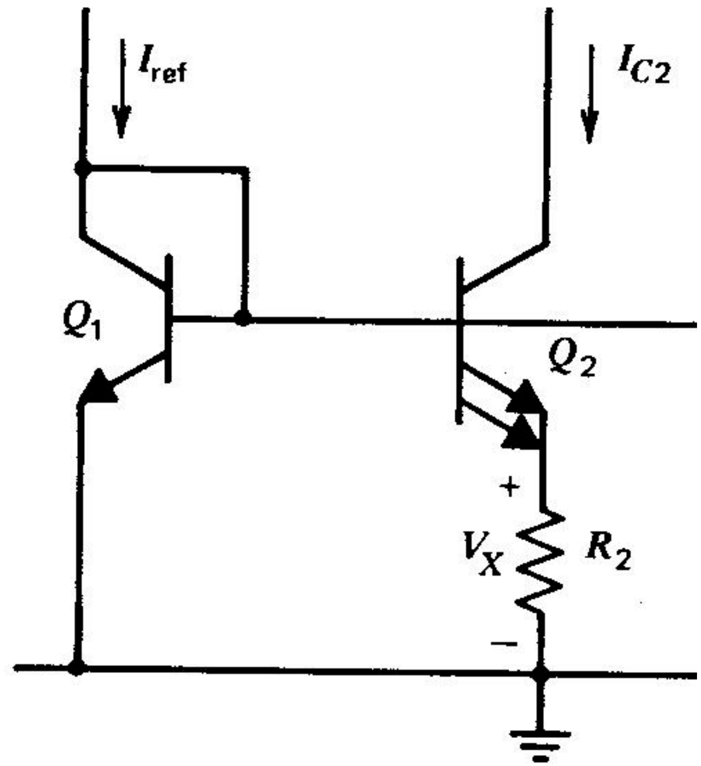
As $TC_F(V_{BE1})$ is –ve and $TC_F(R)$ is +ve, the net TC_F is large => sensitive to temperature with a negative gradient, i.e. as $T\uparrow$, $I_{out}\downarrow$.

V_T-Based Bias Circuit

The difference in the junction potential between two junctions operated at different current densities can be shown to be ∝ to V_T.

From the Widlar current source shown on the right,

$$V_X = I_{C2} R_2 = V_T \ln\left(\frac{I_{C1} I_{S2}}{I_{C2} I_{S1}}\right).$$



If the ratio of the collector currents is constant, then $V_X \propto V_T$. If the emitter area of Q_2 = 2× that of Q_1, then $I_{S2} = 2 \times I_{S1}$.

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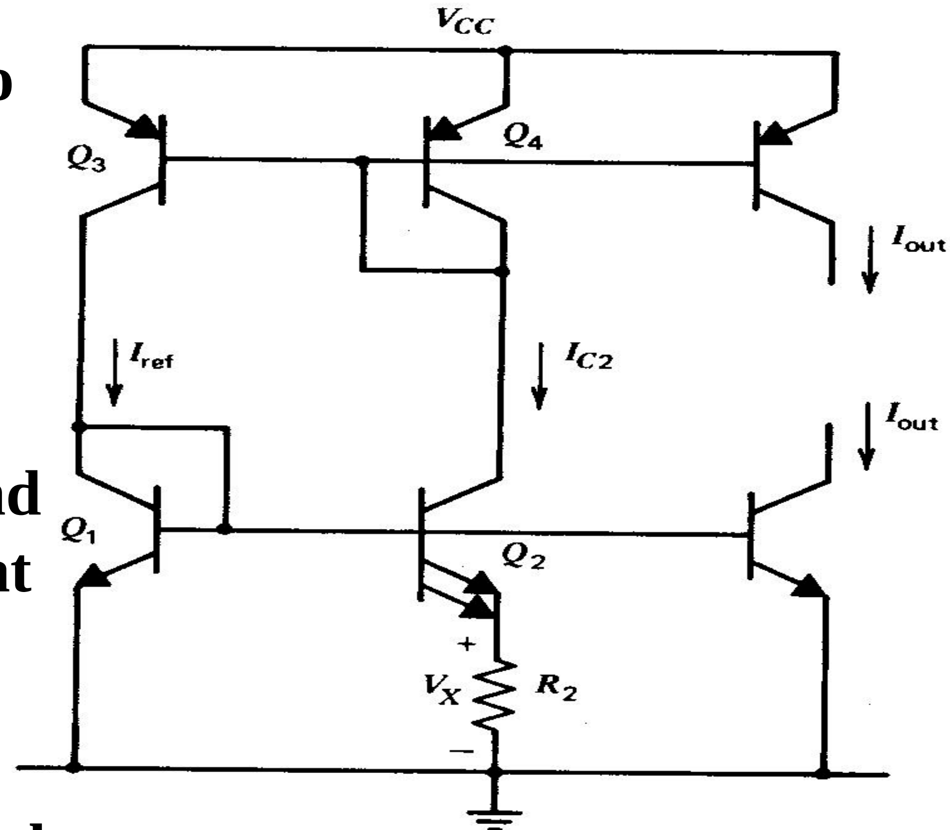
V_T-Based Bias Circuit with Bootstrap



The reference circuit is again made to depend on the current source itself.

Due to the current mirror formed by Q_3 and Q_4, $I_{C1} = I_{C2}$. For Widlar current source: $V_X = V_T \ln 2$.

Satisfying both the current mirror and current source equations requires that

$$I_{C2} = \frac{V_T}{R_2} \ln 2 \ .$$

The output current is supply independent.

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V_T-Based Bias Circuit with Bootstrap

Since $$TC_F = \frac{1}{I_{C2}}\frac{\partial I_{C2}}{\partial T} = \frac{1}{I_{C2}}\frac{\partial}{\partial T}\left(\frac{V_T}{R_2}\ln 2\right) = \frac{1}{I_{C2}}\left(\frac{1}{V_T}\frac{\partial V_T}{\partial T} - \frac{1}{R_2}\frac{\partial R_2}{\partial T}\right)\left(\frac{V_T}{R_2}\ln 2\right)$$
$$= \frac{1}{V_T}\frac{\partial V_T}{\partial T} - \frac{1}{R_2}\frac{\partial R_2}{\partial T}\ .$$

As $TC_F(V_T)$ is +ve and $TC_F(R)$ is +ve, they tend to cancel out! The net TC_F is therefore small => only slightly sensitive to temperature with a positive gradient, i.e. as $T\uparrow$, $I_{out}\uparrow$.

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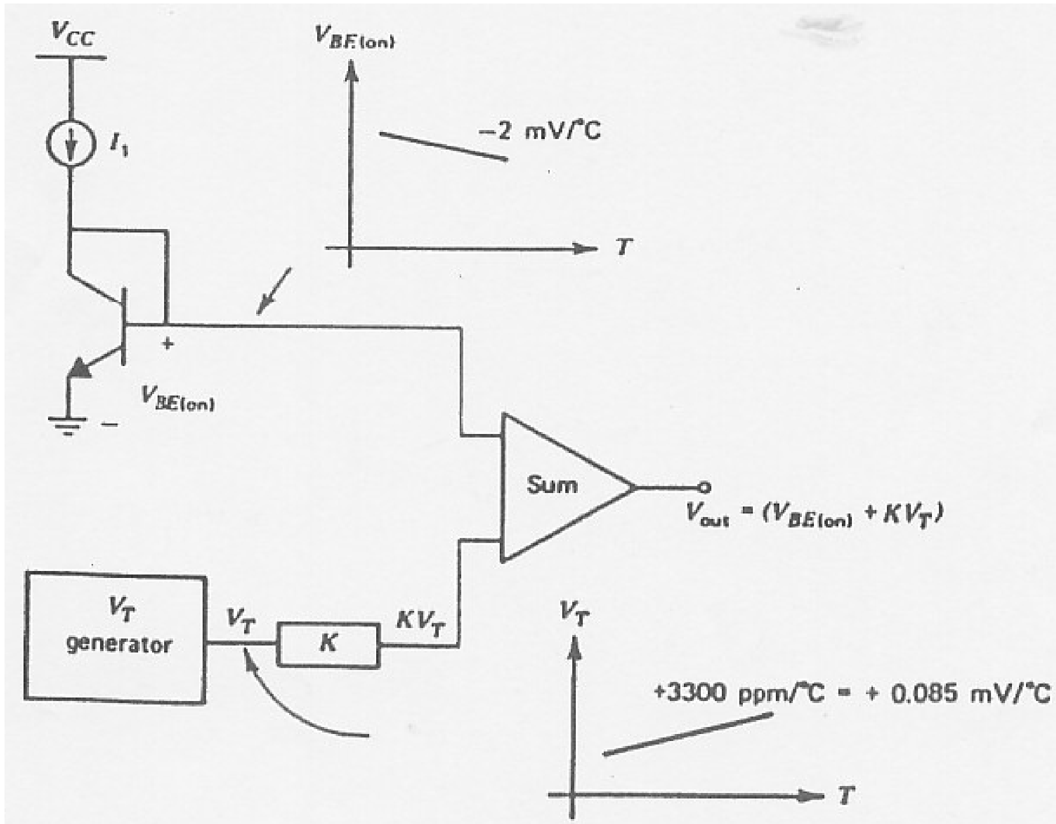
Bandgap Bias Circuit

Notice that the V_{BE}-based and V_T-based reference circuits have opposite TC_Fs, we can obtain a reference current that is a weighted sum of V_{BE}-based and V_T-based reference currents. The idea is that by proper weighting of the currents, we can achieve a reference source with TC_F=0.

$V_{out} = V_{BE} + KV_T$ (K=constant)



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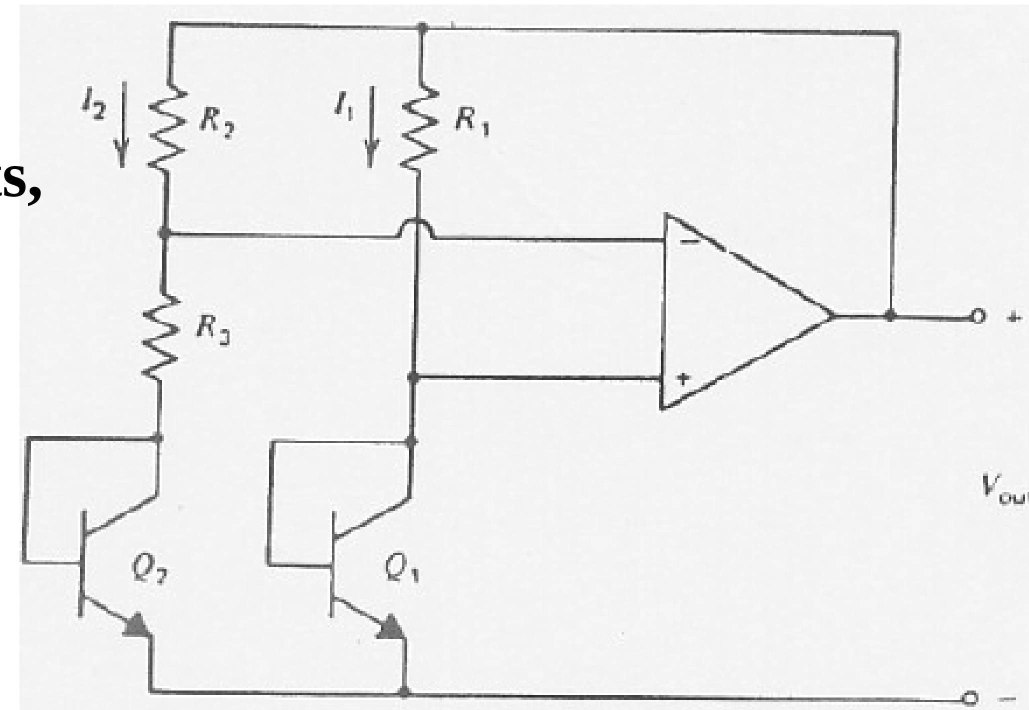
Bandgap Bias Circuit

In an op amp circuit with negative feedback, $V_+ = V_-$.

Hence $V_{R1} = V_{R2}$ and $\dfrac{I_1}{I_2} = \dfrac{R_2}{R_1}$.

Assuming negligible base currents, the difference between V_{BE1} and V_{BE2} is the voltage across R_3.



$$\Delta V_{BE} = V_{BE1} - V_{BE2} = V_T \ln\left(\frac{I_1}{I_2}\frac{I_{S2}}{I_{S1}}\right)$$

$$= V_T \ln\left(\frac{R_2}{R_1}\frac{I_{S2}}{I_{S1}}\right) \quad .$$

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Bandgap Bias Circuit

The voltage across R_2 is $V_{R2} = \frac{R_2}{R_3}\Delta V_{BE} = \frac{R_2}{R_3} V_T \ln\left(\frac{R_2}{R_1}\frac{I_{S2}}{I_{S1}}\right)$ **.**

This means that both I_1 and I_2 are proportional to temperature if the resistors have zero TC_F. The output voltage is the sum of voltages across R_1 and Q_1:

$$V_{out} = V_{BE1} + \frac{R_2}{R_3} V_T \ln\left(\frac{R_2}{R_1}\frac{I_{S2}}{I_{S1}}\right) = V_{BE1} + KV_T \quad \text{where} \quad K = \frac{R_2}{R_3}\ln\left(\frac{R_2}{R_1}\frac{I_{S2}}{I_{S1}}\right).$$

By proper choice of K, V_{out} can be made virtually independent of temperature and supply voltage.

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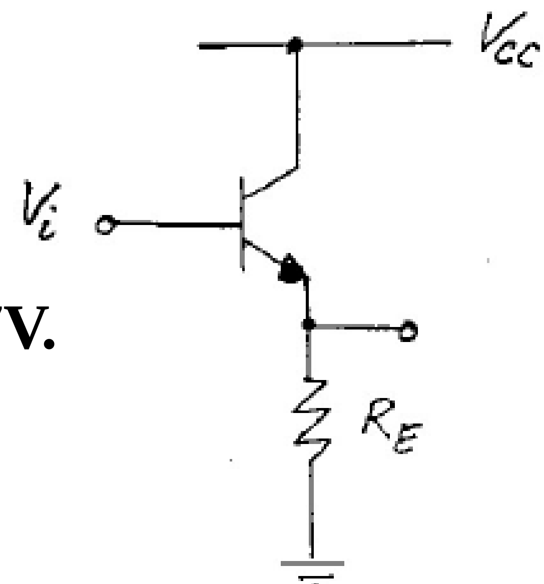
Voltage Level Shifters

Functions of a voltage level shifter: Adjust to specific levels the quiescent voltages at various points of a dc coupled circuit and adjust the output voltage to appropriate quiescent level for optimum swing. The quiescent dc levels in each subcircuit have to be managed as all subcircuits are dc coupled.



By inspection: $V_o = V_i - V_{BEQ} \approx V_i - 0.7\text{V}$.

Two problems: Voltage gain is slightly less than 1.The voltage level shift is limited to only 0.7V.

May use a voltage divider to increase the voltage shift.

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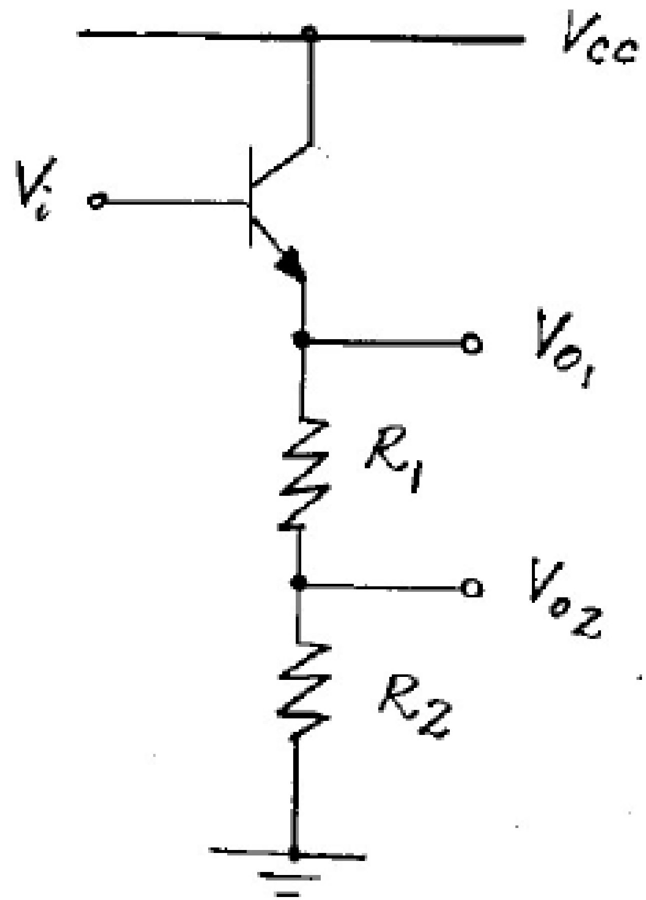
By inspection:

$$V_{o2} = \frac{R_2}{R_1 + R_2}\left(V_i - V_{BEQ}\right).$$

The voltage level shift has increased (by how much?). However, the input signal is attenuated => unacceptable!

Solution: replace R_2 with a current source.



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Voltage Level Shifters

By inspection:

$$V_o = V_i - V_{BEQ} - I \times R_1 \quad .$$

The voltage level shift increases by $I \times R_1$ where I is the biasing current of the current source.

R_1 can be varied to achieve different dc voltage shift.

The ideal impedance of a current source is ∞, hence for any input signal, R_2 is ∞ => no signal attenuation.