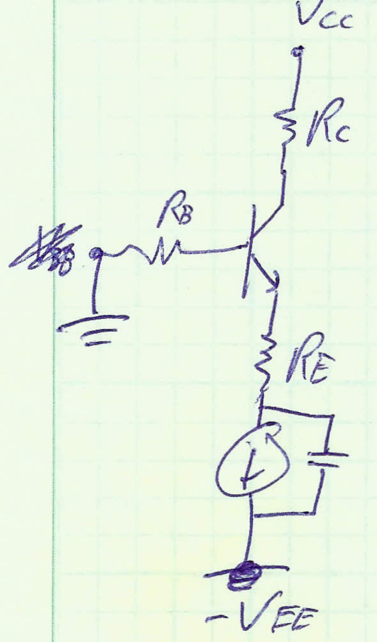
Current Mirrors

- Purpose of stable bias circuit is I_C or I_D independent of transistor parameters and temperature variation
- Can also use current bias

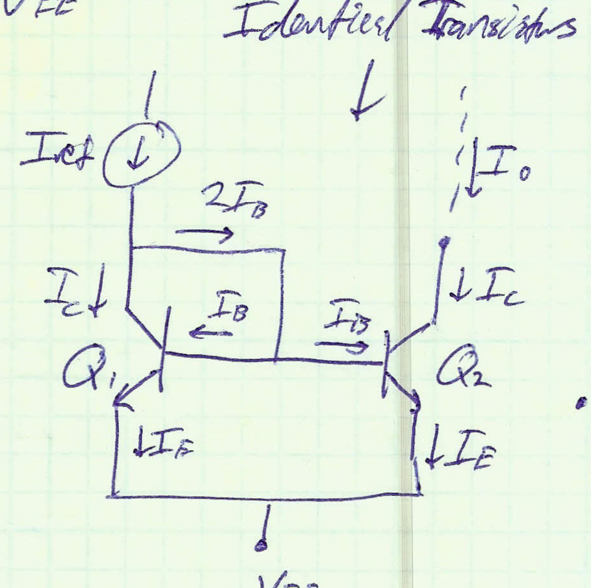


Note that capacitor is needed for signal to pass

Otherwise current would be constant, including AC part

Only necessary for *ideal* current sources

Not needed with the designs we will use



- Q_1 is ON because of I_{ref}
- $V_{CE1} = V_{BE1} = V_{D0} \rightarrow$ active
- $V_{BE2} = V_{BE1} \longrightarrow I_{C2} = I_{C1}$
- If Q_2 also in active state:

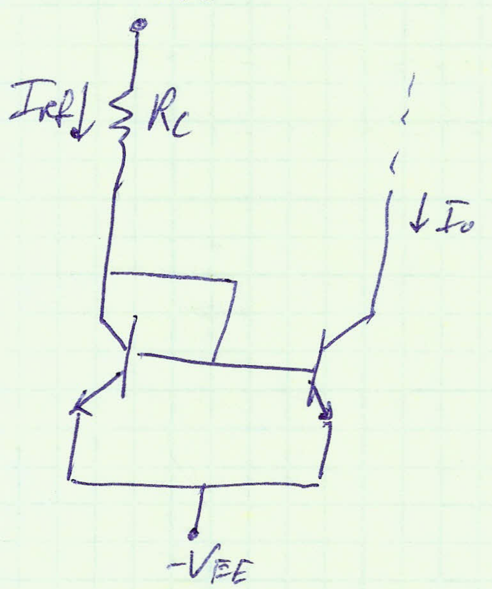
$$I_B = \frac{I_C}{\beta}, \quad I_o = I_C = \beta I_B$$

$$I_{ref} = I_C + 2I_B = (\beta+2) I_B$$

$$\frac{I_o}{I_{ref}} = \frac{\beta}{\beta+2} = \frac{1}{1+2/\beta} \simeq 1$$

- $I_o = I_{ref}$, no matter what is attached to Q_2
- For Q_2 in active state, $\underline{V_{CE2} \text{ must be } \geq V_{D0}}$

Current can be set with simple resistor

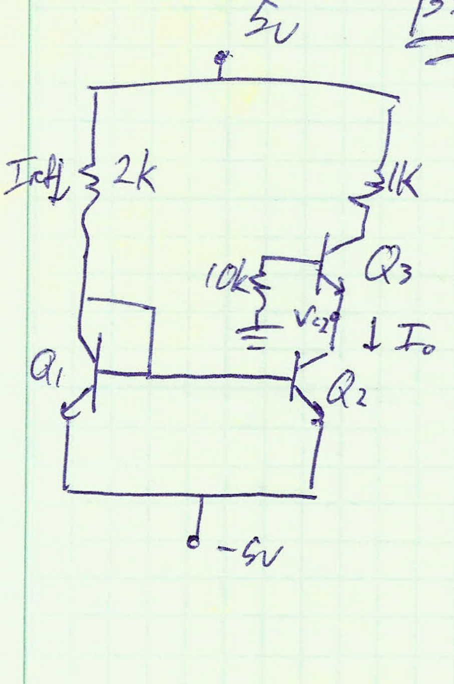


$V_{cc} = I_{ref} R_C + V_{BE1} - V_{EE}$

$I_{ref} = \dfrac{V_{cc} + V_{EE} - V_{D0}}{R_C} = \underline{\text{constant}}$

Example

$\underline{\beta = 100}$



BE1-KVL: $5 = 2k\, I_{ref} + V_{BE1} - 5$

$I_{ref} = 4.65mA$

$I_{E3} \simeq I_o \simeq 4.65mA$

$I_{B3} = \dfrac{I_{E3}}{1+\beta} = 46\mu A$

$I_{C3} = I_{E3} - I_{B3} = 4.6mA$

BE3-KVL: $0 = 10k \cdot I_{B3} + V_{BE3} + V_{C2}$

$\rightarrow V_{C2} = -1.16V$

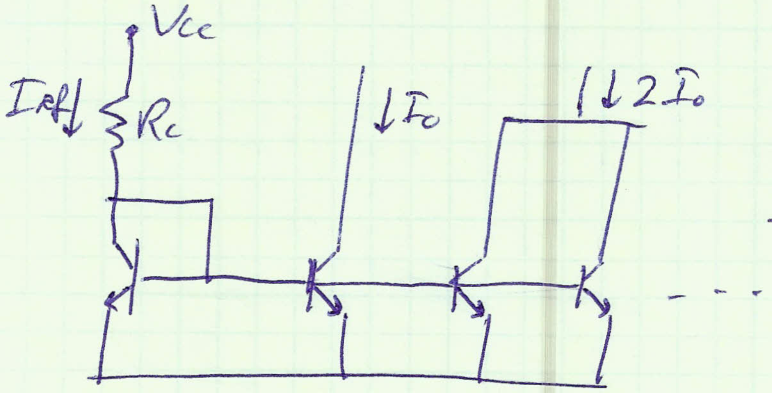
Q_2 is <u>active</u>: $V_{CE2} = V_{C2} - (-5) = 3.84V > V_{D0}$

CE3-KVL: $5 = 1k \cdot I_{C3} + V_{CE3} + V_{C2}$

$\rightarrow V_{CE3} = 1.56V > V_{D0}$

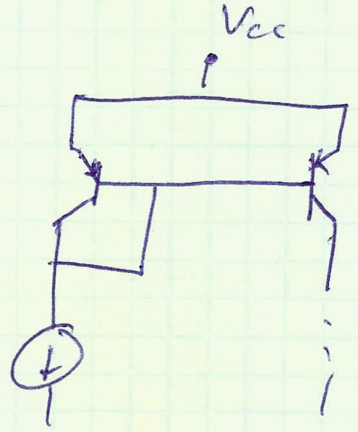
Q_3 is <u>active</u>

Other current mirrors

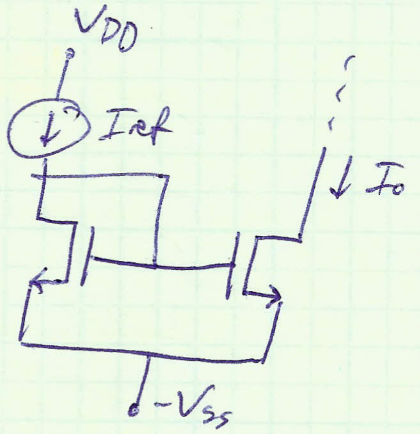


multiple outputs

can also sum currents



PNP version

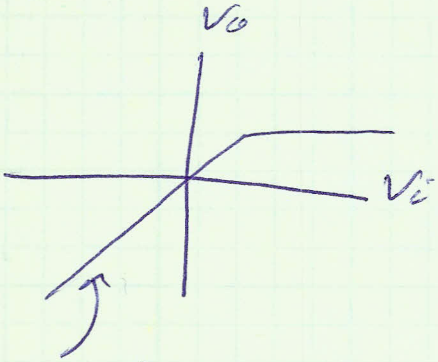


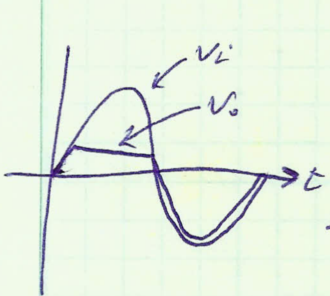
FET version

Small Signal Model

- Nonlinear devices behave as linear in small signal limit

Consider clipper circuit:





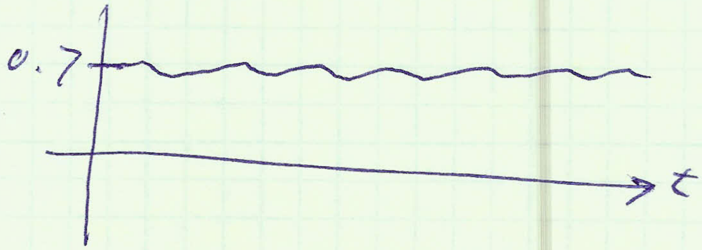
- circuit obviously behaves linearly here
- If we add 2 input voltages, we get sum at output

☆ Even in the clipped region if we add 2 input voltages, we will see <u>something</u> at the output

Example: $V_i = 5 + 0.05 \cos \omega t$

bias · signal

- With our piecewise linear model, $V_o = 0.7V$ always
- In reality, $V_o = 0.6921 + 0.0006 \cos \omega t$ (simulate it!)
- If we double the input signal, $V_i = 5 + 0.1 \cos \omega t$ we get double the output signal: $V_o = 0.6921 + 0.0012 \cos \omega t$



The clipper circuit behaves <u>linearly</u> for small signals

- Sine wave in → Sine wave out
- proportional to input (double input → double output)
- we could also add other frequency components
- this is why we can build linear amplifiers with nonlinear devices
- devices must always be in <u>one state</u>, e.g. ON, active, etc.
- note that any nonlinear function can be approximated by its <u>tangent line</u> for values close to a given point

We can see this from the Taylor series expansion:

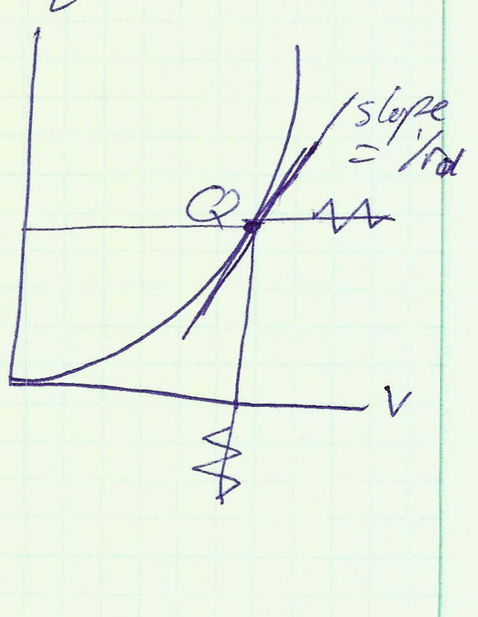
$$f(X_0+\Delta X) = \underline{f(X_0) + \Delta X \frac{df}{dx}\Big|_{x=x_0}} + \frac{(\Delta X)^2}{2!}\frac{d^2f}{dx^2}\Big|_{x=x_0} + \dots$$

If ΔX is small, $(\Delta X)^n$ is small for $n = 2, 3, \dots$

<u>Diode small signal model</u>

$$i_D(V_D+v_d) \simeq i_D(V_D) + v_d \frac{di_D}{dv_D}\Big|_{v_D=V_D}$$

$$= \underbrace{I_D}_{\text{bias current}} + \underbrace{v_d \frac{di_D}{dv_D}\Big|_{v_D=V_D}}_{\text{response to signal}}$$



Diode response to small signal is like a resistor

$i_d = v_d / r_d$

$r_d \equiv \left(di_D / dv_D \big|_{v_D = V_D} \right)^{-1}$

r_d is inverse of slope of tangent line at bias point

find r_d from full expression for diode current:

$i_D = I_S e^{v_D / nV_T}$

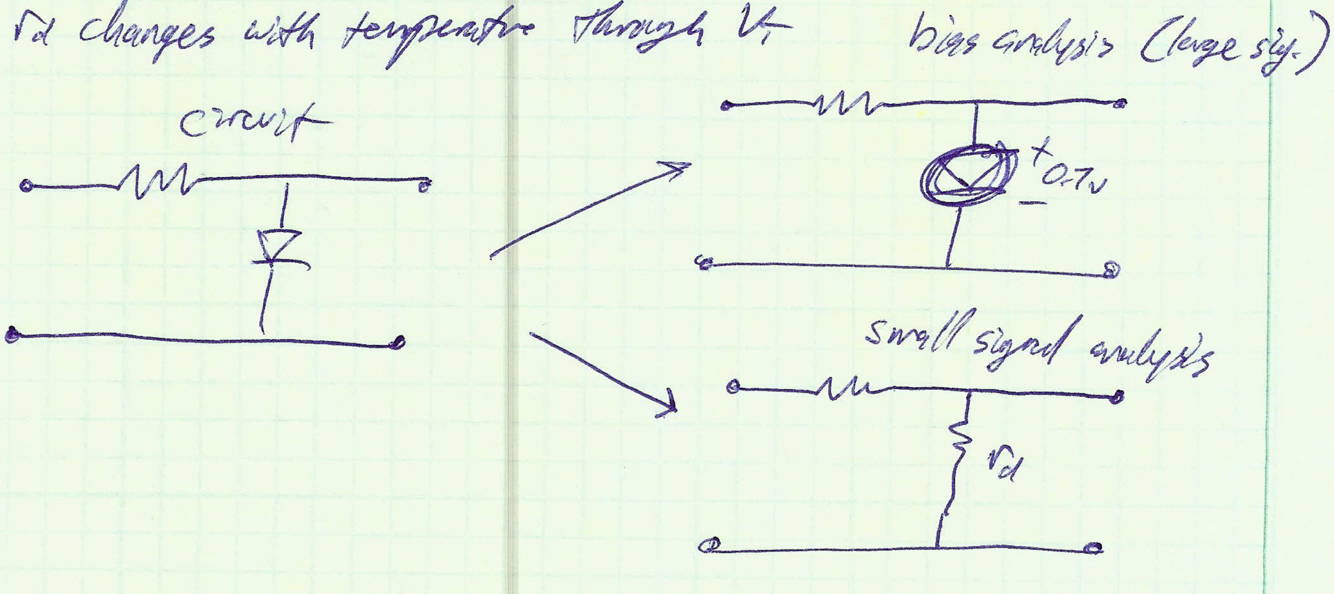
$$\frac{di_D}{dv_D} = \frac{1}{nV_T} \times I_S e^{v_D / nV_T}$$

$$\frac{di_D}{dv_D}\bigg|_{v_D = V_D} = \frac{1}{nV_T} I_S e^{V_D / nV_T} = \frac{I_D}{nV_T}$$

$$r_d = \frac{nV_T}{I_D}$$

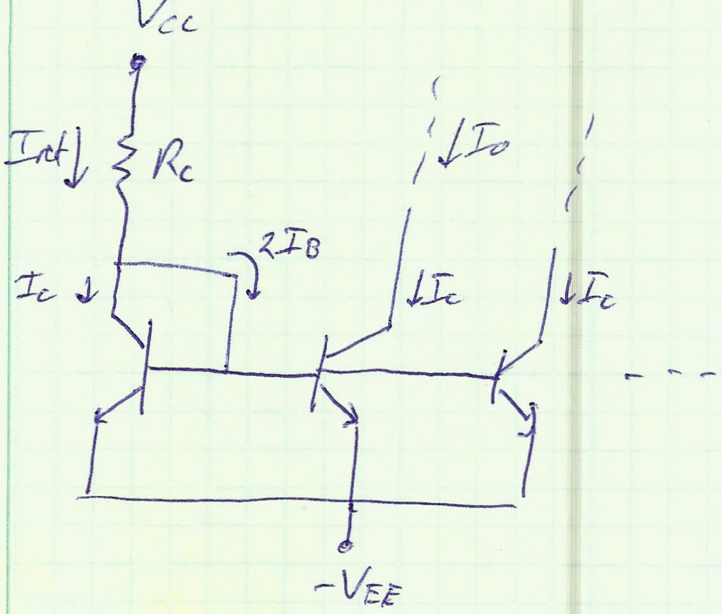
$\uparrow$ I_D is the bias current

r_d changes with temperature through V_T



Current Mirrors

Summary



for single current mirror

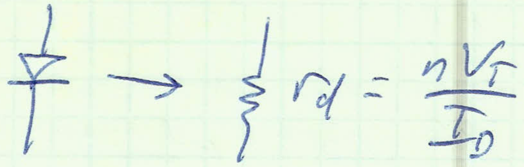
$$\frac{I_O}{I_{ref}} = \frac{\beta}{\beta+2}$$

I_O can be multiplied by using multiple transistors at output

- MOSFET current mirror is similar but we can scale W/L instead of using multiple transistors

Diode Small Signal Model

In on state:



$$r_d = \frac{n V_T}{I_D}$$

I_D is DC bias current

$n = 2$ for discrete silicon diodes

$V_T = 25mV$ at 300k