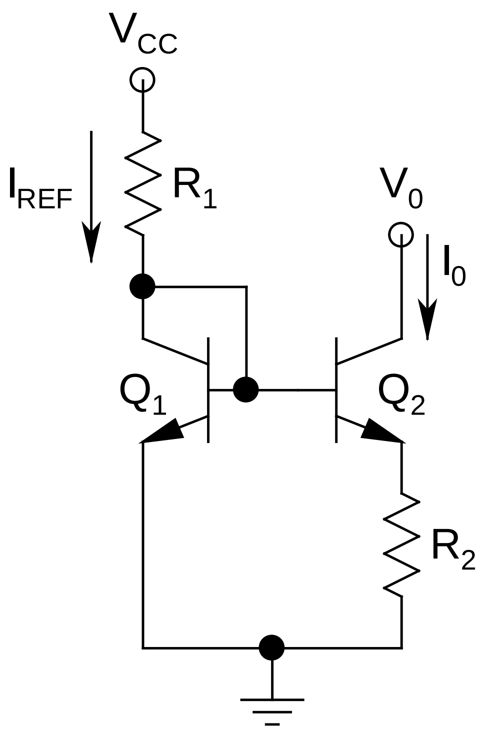
- ***Double Cascode***:
  - ***Can be implemented in both BJT & MOS***
  - ***In npn Double Cascode***, ***another pair Q_5-Q_6 stacked upon Q_3-Q_4***
    - ***Find $V_{0,min}$ and R_0***
  - ***In NMOS Double Cascode***, ***another pair M_5-M_6 stacked upon M_3-M_4***
    - ***Find $V_{0,min}$***
    - $R_0 \approx g_{m6} r_{06} R_0$ ($R_0 \approx g_{m4} r_{02} r_{04}$)
  - ***Hence, show that double cascode in BJT offers absolutely no advantage in terms of R_0***

- ***Low Value Current Source***:
  - ***Current thrust***: ***Low-power circuits***

    $\Rightarrow$ ***Increase in battery life***
  - ***If bias current can be reduced from mA to*** μ***A***, ***for the same power supply voltage***, ***power drawn reduces by three orders of magnitude***!
  - ***Normal CMs can also produce bias current in*** μ***A range***, however, ***the required resistance will be huge*** $\Rightarrow$ ***uneconomical for ICs***
  - ***Most common***: ***Widlar Current Source***
    - ***After its inventor Bob Widlar*** (***father of op-amp***)

- ***Widlar Current Source***:
  - ***Q_1-Q_2 matched pair***
  - $I_{REF} = (V_{CC} - V_{BE1})/R_1$
  - If $I_0 = I_{REF}$, then $V_{BE1} = V_{BE2}$
    - ***No drop across R_2***!

      $\Rightarrow I_0 \neq I_{REF}$
  - ***Actually, the difference between V_{BE1} and V_{BE2} drops across R_2***



- ***KVL around Q_1-Q_2 BE loop***:

$$V_{BE1} = V_{BE2} + I_0R_2$$

$$\Rightarrow I_0 = \frac{V_{BE1} - V_{BE2}}{R_2} = \frac{V_T}{R_2}\ln\left(\frac{I_{REF}}{I_0}\right)$$

(***since $I_{S1} = I_{S2}$***)

- ***Transcendental equation in I_0***
- ***If I_0 is known***, ***finding R_2 is absolutely easy***!
- On the other hand, ***if R_2 is given***, ***to find I_0***, ***need to iterate***, ***but the solution will converge rapidly*** (***Why***?)

- ***The ln function compresses a large difference between I_{REF} and I_0 into a small range***
  - For I_{REF} ~ mA, I_0 ~ μA, with R_1 ~ few kΩs and R_2 ~ few 10s of kΩ

    ⇒ ***Significant flexibility***!
- $V_{0,min} = V_{CE2}(SS) + I_0R_2$

  ~ ***0.3-0.4 V for practical values of I_0 and R_2***
- ***R_0 can be obtained by sheer inspection of the circuit by noting that the base of Q_2 is approximately at ac ground***
- Also, $r_{\pi 2} >> R_2$ (***Why***?)

- Thus,

  $R_0 \approx r_{02}(1 + g_{m2}R_2)$

- ***Note***: ***To approximate this as $g_{m2}r_{02}R_2$, first make sure that $g_{m2}R_2 >> 1$*** (***may not be***!)

- ***Actual expression***:

  $R_0 \approx r_{02}(1 + g_{m2}R_{eff})$ with $R_{eff} = R_2 \| r_{\pi 2}$

- ***During further simplification***, ***always check the validity of your assumption/approximation***
  - *Otherwise it may lead to large errors*!

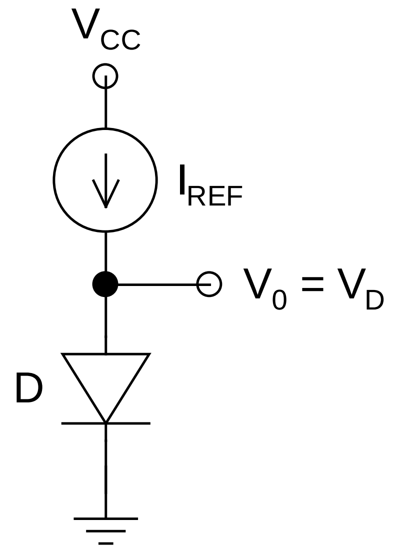
- ***Counterpart of this circuit in MOS technology does not exist*** (***Why***?)

DC Voltage References

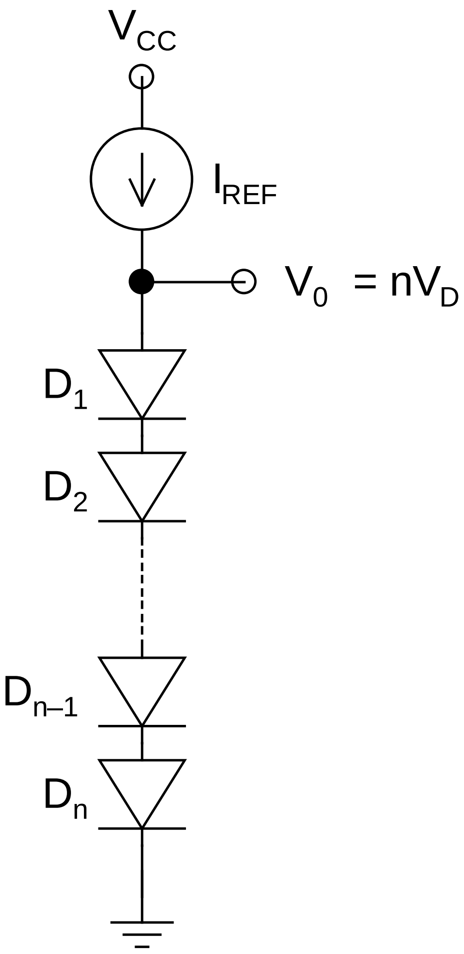
- ***Along with current sources/sinks***, ***also need stable and precise DC voltage references***
- ***Provides DC bias voltages at specific points of the circuit***
- ***Should be independent of power supply and temperature***
- ***Can range from –ve to +ve power supplies***
- ***On-Chip***: ***Generated within the chip itself***

- ***In ICs***, ***diodes are not fabricated as such***
  - ***BJTs are used as diodes by shorting their Base and Collector terminals***
- ***Various Voltage References***:
  - ***Single Diode Reference***
  - ***Multiple Diode Reference***
  - V_{BE} ***(or*** V_D***) Multiplier***
  - ***Saturated Transistor***
  - ***NMOS Voltage Reference***

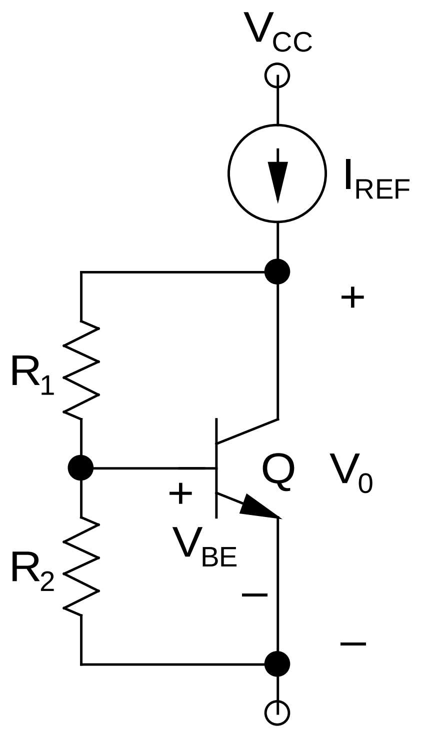
- ***Single Diode Reference***:
  - I_{REF}: ***DC Bias Current***
  - ***Creates a voltage drop of V_D (or V_{BE}) across the diode of ~ 0.7 V***
  - ***Known as V_{BE} (or V_D) Reference***
  - ***Precision quite poor***
  - ***Thermal tracking poor***



- ***Multiple Diode Reference***:
  - ***Putting multiple diodes in series***
  - ***DC bias current I_{REF} pushed through them***
  - ***Each diode creates a drop of V_D across it***
  - ***Has same problems as Single Diode Reference***
  - ***Note***: ***n can only be an integer***



- ***V_{BE} (or V_D) Multiplier Circuit***:
  - ***Previous two circuits provide $V_0 = nV_D$, with n being an integer ≥ 1***
  - ***For any arbitrary value of n (≥ 1), this circuit becomes useful***
  - ***Immensely popular because of its simplicity and effectiveness***
  - ***Biased by a DC current source I_{REF}***



- ***Neglecting base current***:

$$V_{BE} = \frac{R_2}{R_1 + R_2} V_0$$

$$\Rightarrow V_0 = \left(1 + \frac{R_1}{R_2}\right) V_{BE}$$

$\Rightarrow$ ***V_{BE} Multiplier*** with ***multiplication factor $(1 + R_1/R_2)$***

- ***Any arbitrary ratio of R_1 and R_2 can be used***, ***but the multiplication factor is always ≥ 1***

- ***Least possible $V_0 = V_{BE}$*** [***$R_1 = 0$*** (***short-circuit***) and ***$R_2 \rightarrow \infty$*** (***open-circuit***)]

  $\Rightarrow$ ***Diode-Connected BJT***
- ***The term*** **$(1 + R_1/R_2)$** ***has excellent thermal tracking***, ***since the TC_F of R_1 and R_2 cancel each other***, ***but the TC_F of V_{BE} remains***
- ***So far, we have got voltage references having $V_0 \geq V_{BE}$***
- ***How to have a voltage reference having $V_0 < V_{BE}$?***

- ***Saturated Transistor***:
  - ***Neglecting base current***:

    $V_0 = V_{BE} - I_{REF}R$
  - ***Note***: ***V_0 is actually V_{CE}***, ***which is < V_{BE}***

    $\Rightarrow$ ***Q saturated***

    $\Rightarrow$ ***Analysis highly approximate***, ***since base current can't be neglected in saturation***
  - ***Typical range of V_0 ~ 0.2-0.7 V***