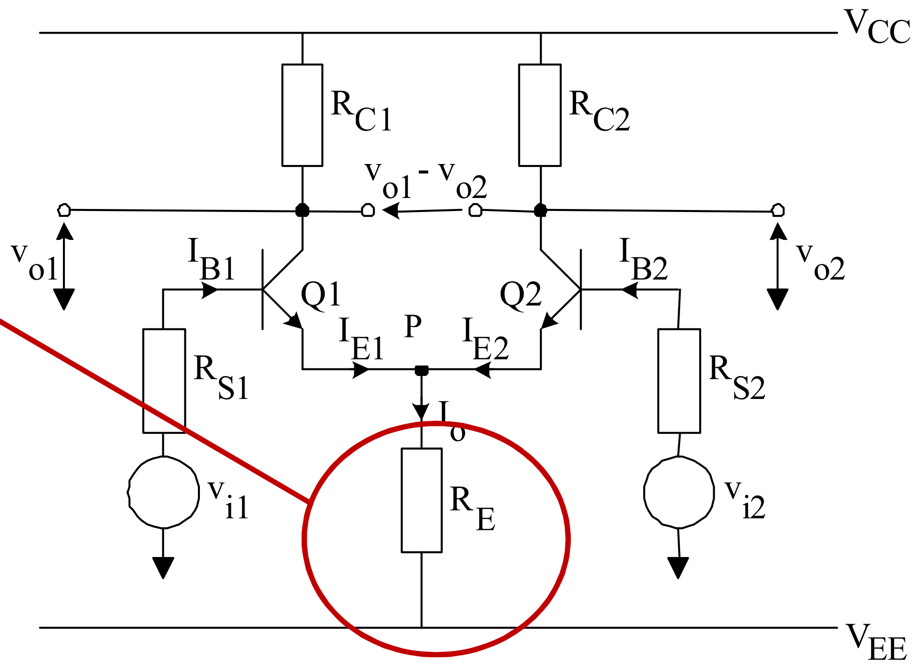
Electronic circuits and systems
ELEC271

Part 4
Current sources

Active circuits for biasing
how they work
design issues

Recall the 'problems' with the Diff Amp



We require

- **a better bias circuit to replace R_E, which will allow us to set the current I_o, independently of the resistance in the 'tail'.**

- **We would also like such a bias circuit to exhibit a very large dynamic resistance to give high common mode rejection ratio (CMRR).**

$$A_C \sim 1/R_E$$

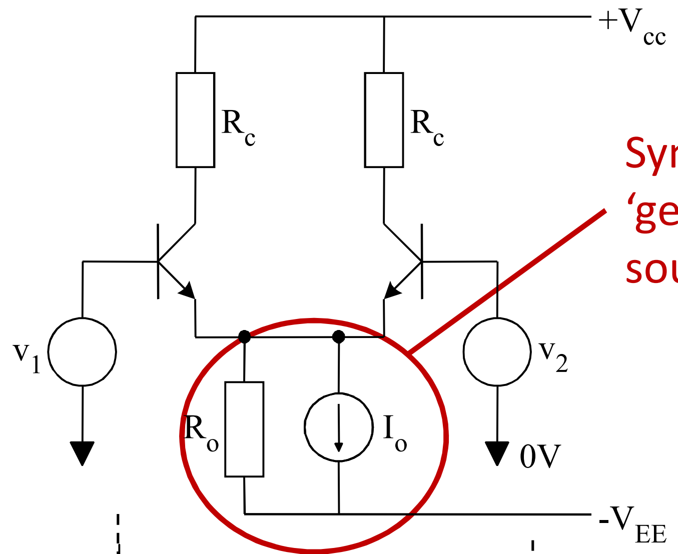
- ***a circuit to replace the collector resistors, which will present a high resistance (for high gain) without creating a large voltage drop which causes the transistors to saturate and upsets the symmetry of the voltage swing.***

$$A_d = -20 I_o R_C$$

$$I_o \sim V_{EE}/R_E$$

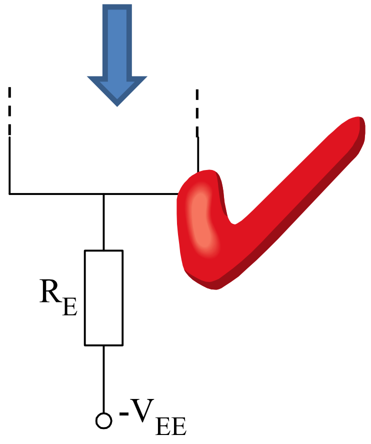
Diff. Amp with Constant current source biasing

3 types of current source

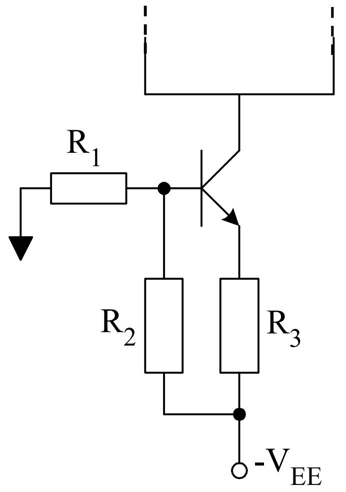


Symbols for a 'generic' current source

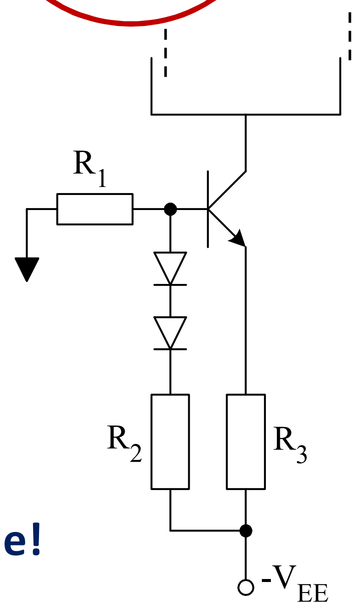
Already studied this one



Simple current source formed by R_E and V_{EE}

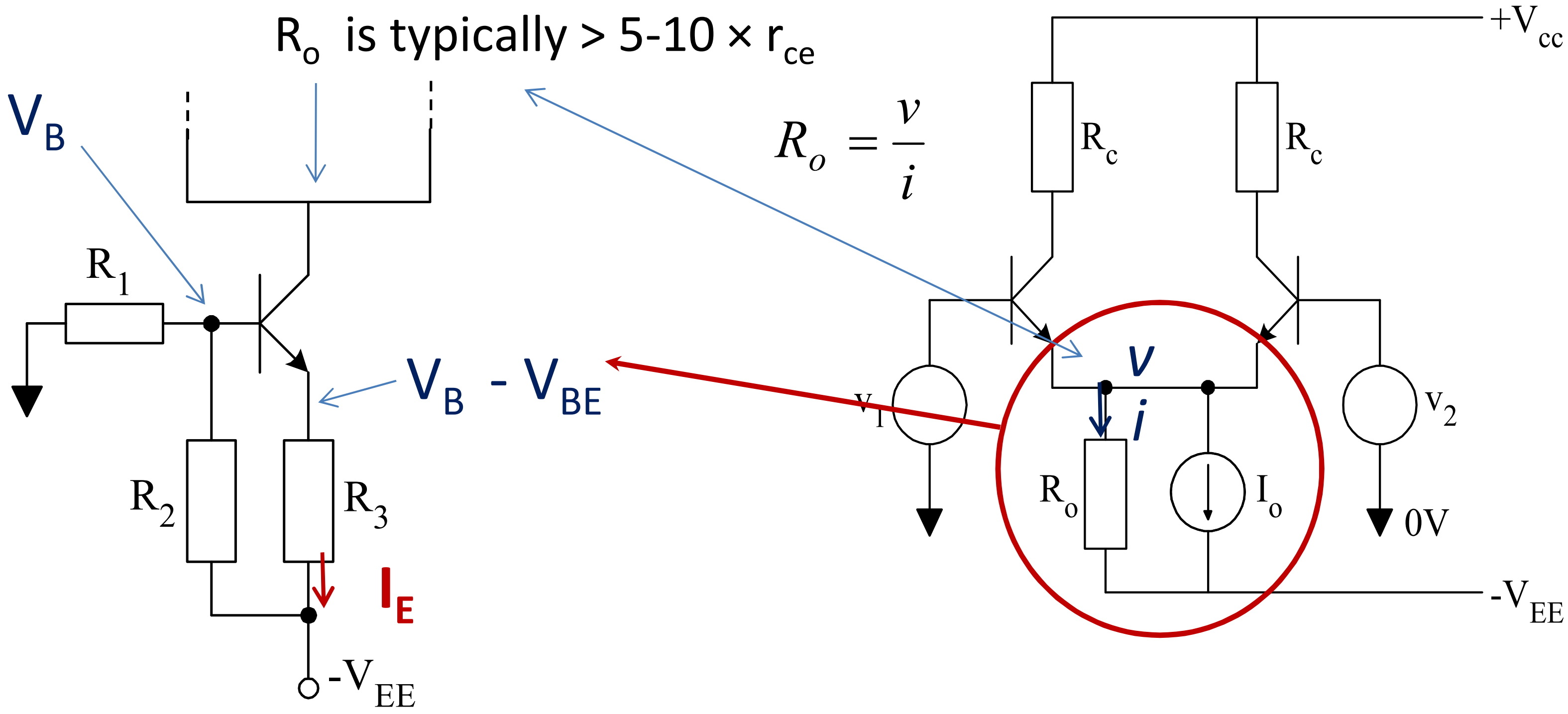


A much better one!



A much better one that's temperature compensated!

How it works and design



$$V_B \sim -V_{EE}\frac{R_1}{R_1+R_2}$$

$$I_E = \left|\frac{\left(|V_B| - V_{BE}\right) - |V_{EE}|}{R_3}\right| \sim I_C = I_o$$

By potential division
(assuming $I_B \sim 0$

Exercise: try drawing an ac equivalent circuit!

How it works: large R_o

Consider a slight increase in voltage, ΔV

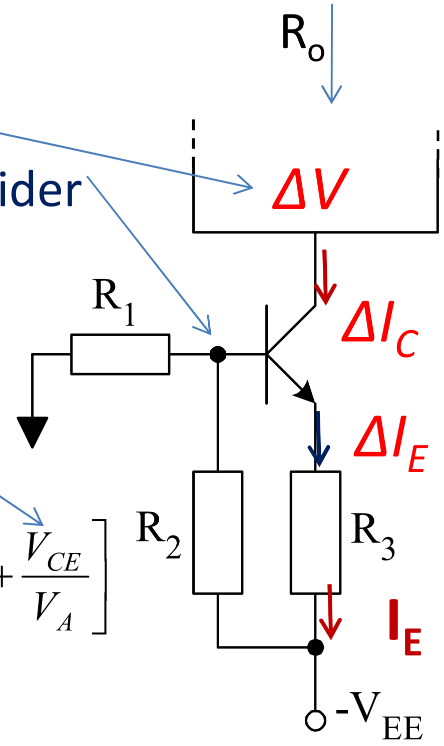
Will get slight increase, ΔI_C (Early effect) and hence ΔI_E .

Hence a slight increase in emitter voltage

and hence a slightly smaller V_{BE} for the transistor!

which in turn causes I_C to decrease.

V_B
Fixed by potential divider R_1 , R_2



$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)\left[1+\frac{V_{CE}}{V_A}\right]$$

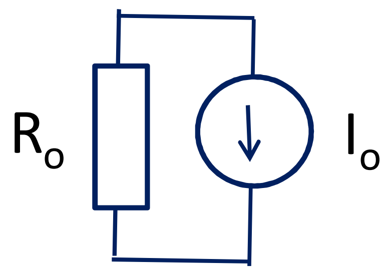
That is to say, the resistor R_3 provides **'feedback'** and prevents I_C and hence I_O rising. This is the physical effect that gives rise to very large R_o.

Net result? – a tiny increase in collector current

$$R_o = \frac{\Delta V}{\Delta I}$$

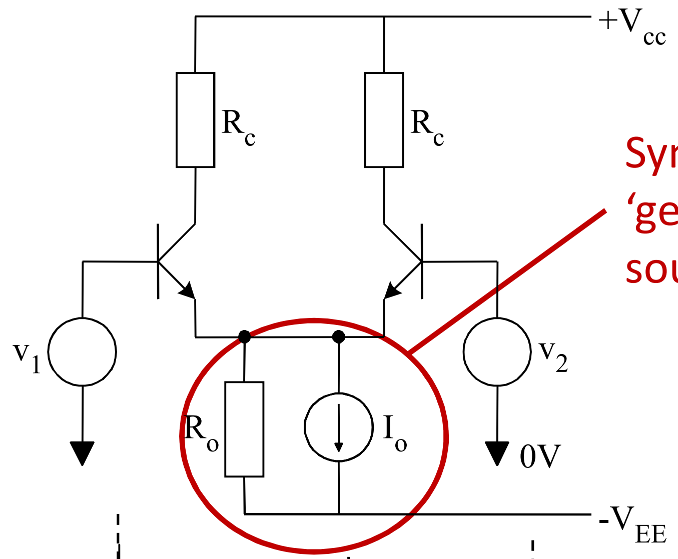
Very large

$\Delta V = v$
$\Delta I = i$
Ac quantities



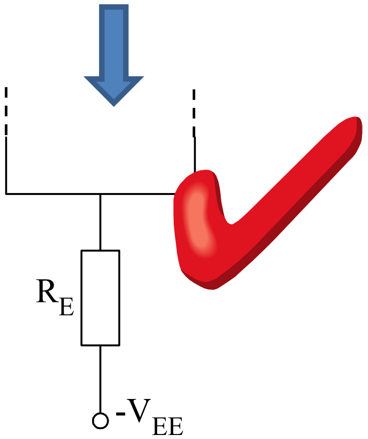
Diff. Amp with Constant current source biasing

3 types of current source

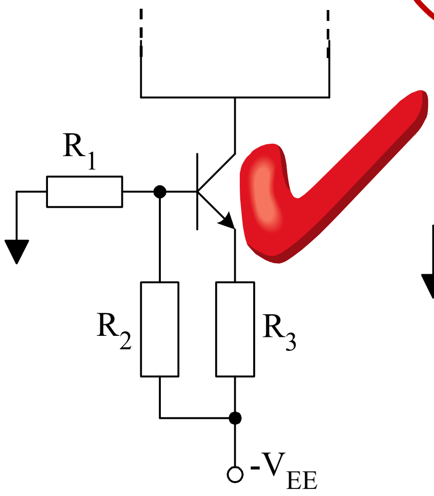


Symbols for a 'generic' current source

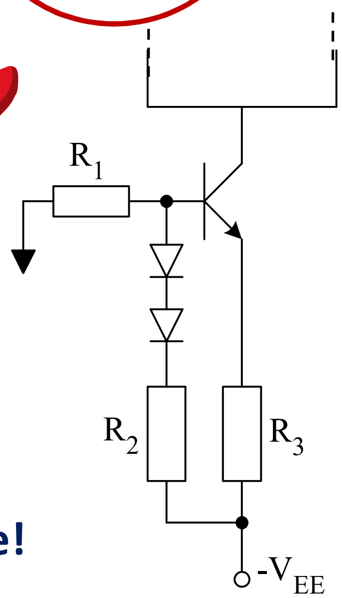
Already studied this one



Simple current source formed by R_E and V_{EE}



A much better one!



A much better one that's temperature compensated!

3rd circuit: temperature compensated

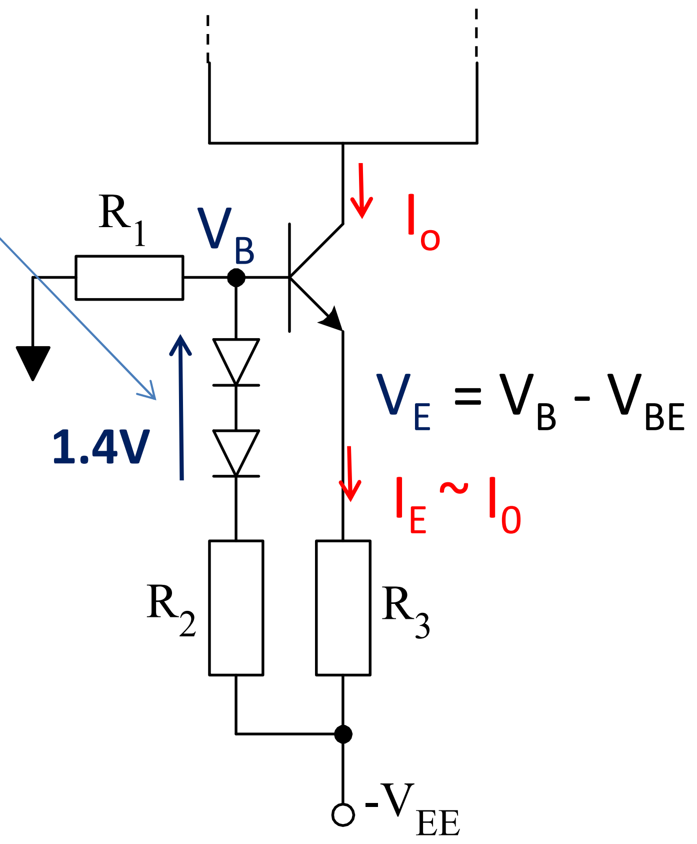
Design equations

2 diode drops

$$V_B \sim -\left(\left|V_{EE}\right| - 1.4\right)\frac{R_1}{R_1 + R_2}$$

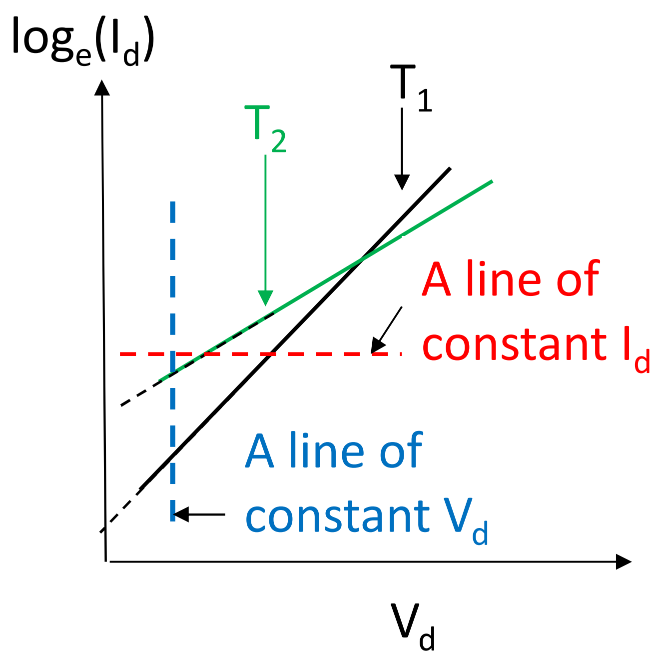
$$V_E \sim -\left(\left|V_{EE}\right| - 1.4\right)\frac{R_1}{R_1 + R_2} - V_{BE}$$

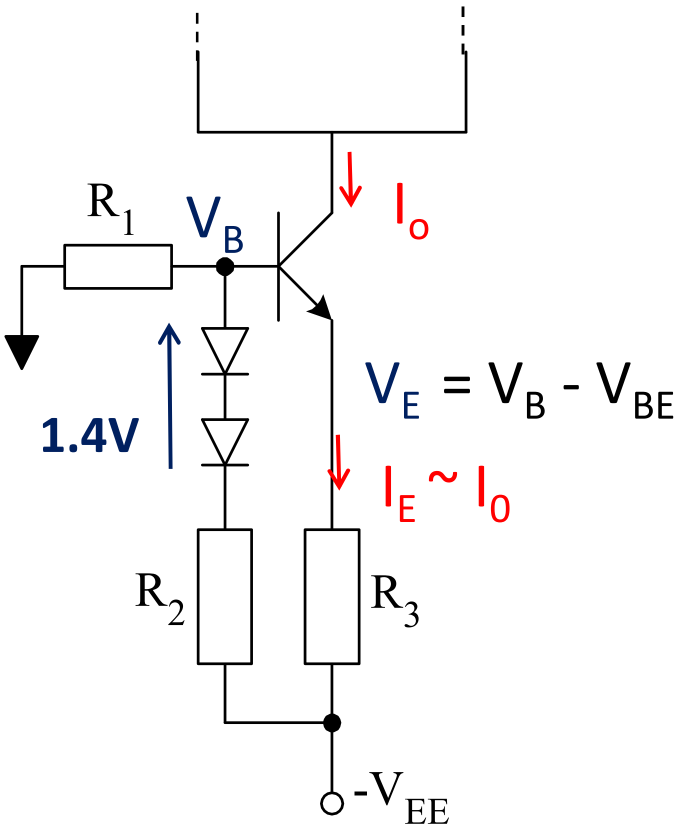
$$I_E = \frac{\left(\left|V_{EE}\right| - \left|V_E\right|\right)}{R_3} \sim I_C = I_o$$



Why the diodes?

Consider diode characteristics at
2 temperatures, T_1 ,T_2





$$I_d = I_S(T)\exp\left(\frac{qV_d}{kT}\right)$$

$$V_d = \frac{kT}{q} ln\left(\frac{I_d}{I_S(T)}\right)$$

$$\frac{\partial I_C}{\partial T} \propto Const\frac{\partial V_{diodes}}{\partial T} - \frac{\partial V_{BE}}{\partial T}$$

As T↑,
I ↑ (for constant V)
and V↓ (for constant I)

Diodes provide 'temperature compensation'
Prevent I rising much as T rises

Temperature compensation - analysis

n diode drops

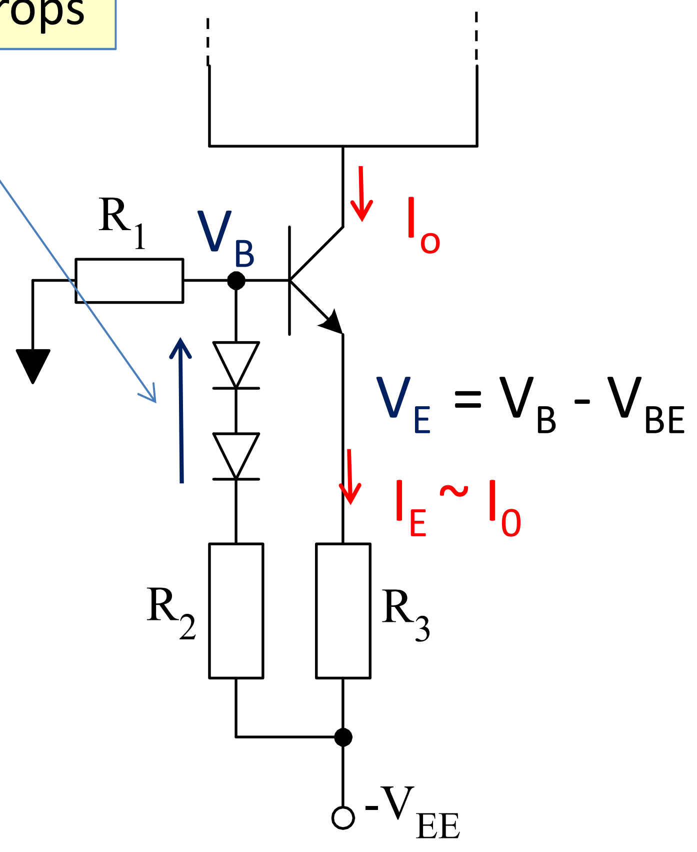
$$V_B \sim -\left(\left|V_{EE}\right| - n \times V_d\right)\frac{R_1}{R_1 + R_2}$$

$$V_E \sim -\left(\left|V_{EE}\right| - n \times V_d\right)\frac{R_1}{R_1 + R_2} - V_{BE}$$

$$\frac{dV_E}{dT} \sim n \times \frac{dV_d}{dT}\frac{R_1}{R_1 + R_2} - \frac{dV_{BE}}{dT}$$

$$I_E = \frac{\left(\left|V_{EE}\right| - \left|V_E\right|\right)}{R_3} \sim I_C = I_o$$

$$\frac{dI_o}{dT} = -\frac{1}{R_3}\frac{dV_E}{dT}$$

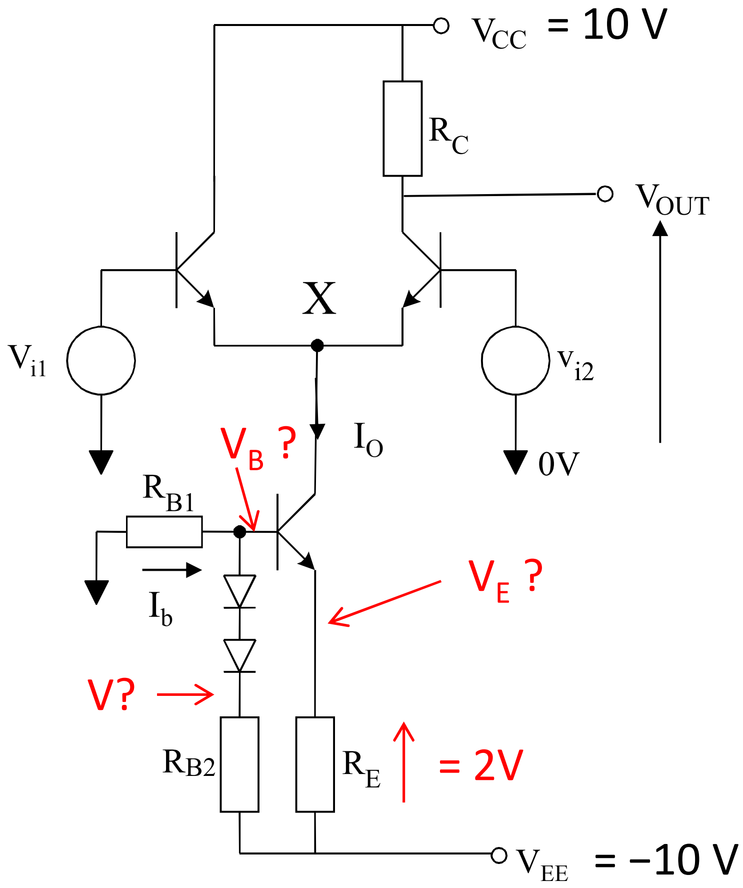


$$\Rightarrow \quad \frac{dI_o}{dT} \sim -\frac{1}{R_3}\left(n \times \frac{dV_d}{dT}\frac{R_1}{R_1 + R_2} - \frac{dV_{BE}}{dT}\right)$$

Design: Aim to make the 2 temperature dependent terms on the RHS equal so that dI_O/dT tends to 0

Worked example (Summer 2018 exam)

Design the circuit to meet the specification:
I_O = 1 mA, DC level at V_{OUT} = 0 V.
Hints: Allow 2 V across R_E, Ib = 0.1× I_O
ideal transistors with high DC current gain.



Solution

I_b $= 0.1\times IO = 0.1$ mA

R_E ? $R_E = \dfrac{2}{1mA} = 2\ k\Omega$

V_E ? $V_E = -10 + 2 = -8\ V$

V_B ? $V_B = -8V + 0.6 = -7.4\ V$

R_{B1} ? $R_{B1} = \dfrac{0-(-7.4)}{0.1mA} = 74\ k$

V? $\mathrm{V} = -7.4 - 2\times 0.6 = -8.6$

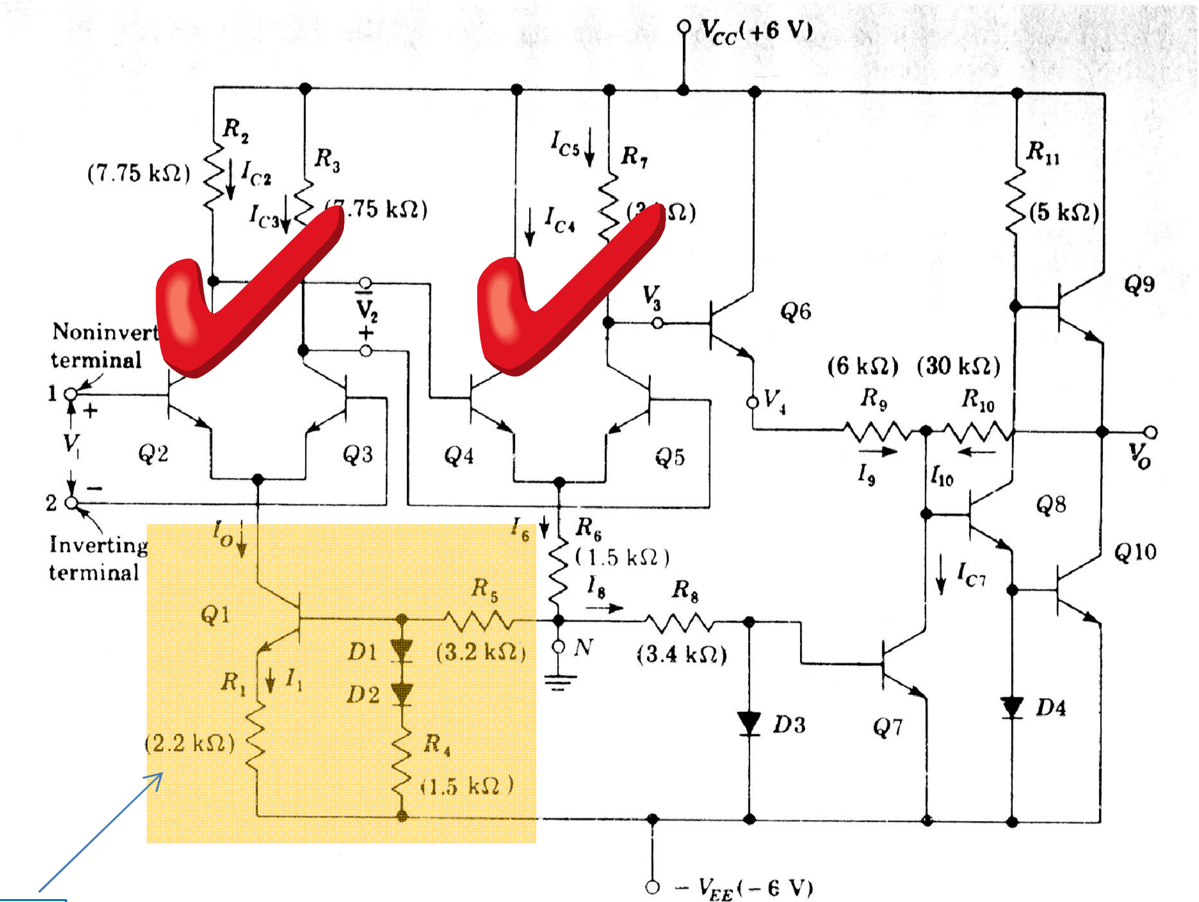
R_{B2} ? $R_{B2} = \dfrac{-8.6-(-10)}{0.1mA} = 14\ k\Omega$

$$Diff\ Gain = \frac{g_m \times R_C}{2}$$

A target for week 4...

By about week 4 we will be able to:

- Identify circuit 'building blocks'
- Perform a dc analysis to estimate all currents and voltages
- Perform an ac analysis to estimate gain of amplifier



Temperature compensated current source which provides the biasing

Motorola MC1350 operational amplifier

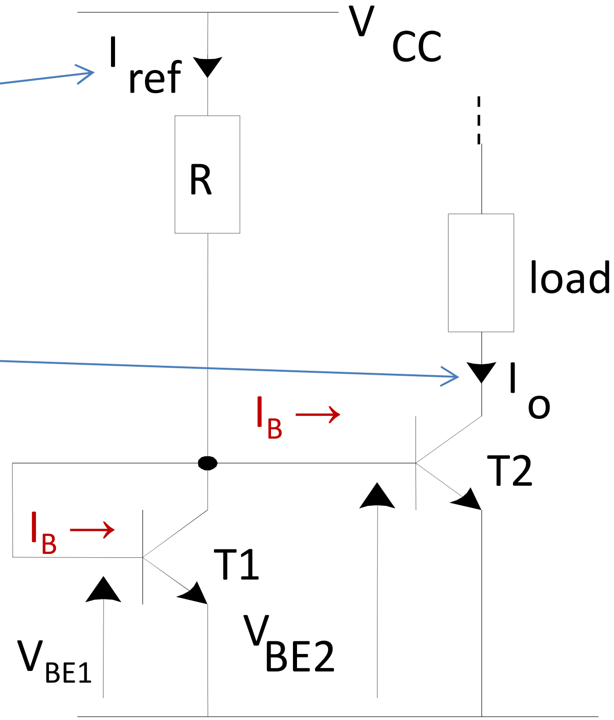
Further biasing techniques

- Current mirrors and current repeaters

Simple current mirror

- $V_{BE1} = V_{BE2}$
- assume transistors are identical
- **So $I_{C1} = I_{C2} = I_O$**

$$\boxed{I_C = I_S \exp\left[\frac{V_{BE}}{V_T}\right] \qquad V_T = \frac{kT}{q} \sim 25mV}$$



$$I_{ref} = I_{C1} + 2I_B = I_C + 2\frac{I_C}{\beta}$$

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

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

$\beta \equiv h_{FE}$ large!

$$I_{ref} = \frac{V_{CC} - V_{BE}}{R}$$

- Set I_{ref} choosing R - current is 'mirrored' in T_2 to provide I_O.
- a number of current sources can be created to provide bias in different parts of a more complex circuit as shown on next slide......

A current 'repeater'

$$I_C = I_S \exp\left[\frac{V_{BE}}{V_T}\right]$$

$$I_{ref} = \frac{V_{CC} - V_{BE}}{R}$$

$I_c = I_o$

$$I_{ref} = I_B + NI_B + I_o$$

- it's easy to show that

$$I_o = \frac{I_{ref}}{1+(N+1)/\beta}$$

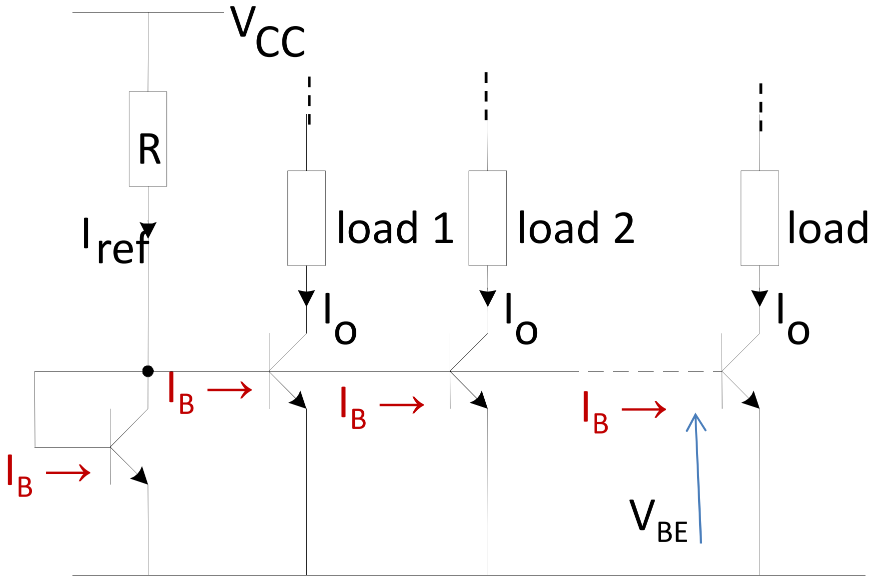
- **But all bias currents are the same!**
- Could make the transistor larger; that is make I_S larger by factor 'n'

$$I_{C1} = I_{S1} \exp\left(\frac{V_{BE}}{V_T}\right)$$

$$I_{C2} = I_{S2} \exp\left(\frac{V_{BE}}{V_T}\right)$$

I_S ~ device area

$$\frac{I_{C1}}{I_{C2}} = \frac{I_{S1}}{I_{S2}} = n \qquad I_o = nI_{ref}$$



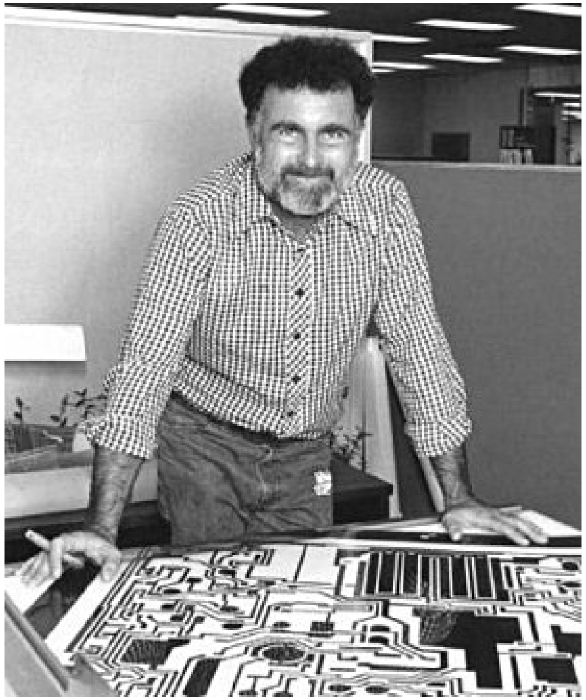
small values of 'n' can be produced this way but bias currents may differ by factors of ten and more...

so the transistors would have be very large.

A better way to scale the bias currents is to use a **'Widlar'** current mirror.

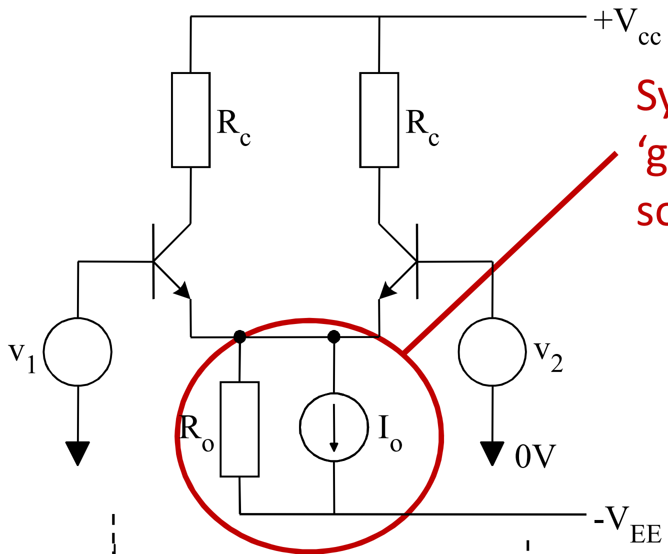
Who is 'Widlar'?

- a pioneer of linear (analog) integrated circuit (IC) design. **Bob Widlar** invented the basic building blocks of linear ICs like the
- Widlar current source
- Widlar bandgap voltage reference
- Widlar output stage
- From 1964 to 1970, Widlar, together with David Talbert, created the first mass-produced operational amplifiers ICs (µA702, µA709), the first integrated voltage regulator IC (LM100), the first operational amplifiers employing full internal compensation (LM101), field-effect transistors (LM101A), and super-beta transistors (LM108). **Each of Widlar's circuits had "at least one feature which was far ahead of the crowd" and became a "product champion" in its class.**
- They made his employers, Fairchild Semiconductor and National Semiconductor, the leaders in linear integrated circuits.



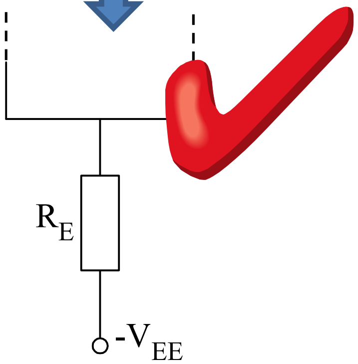
Diff. Amp with Constant current source biasing

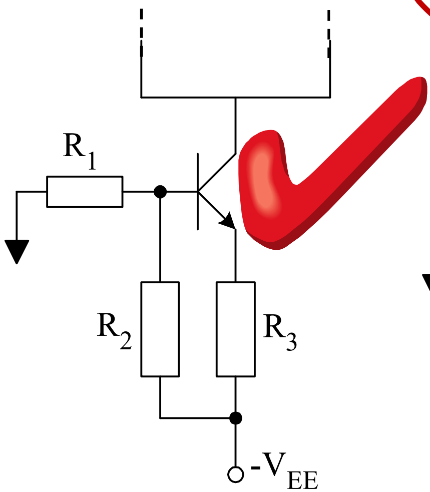
3 types of current source

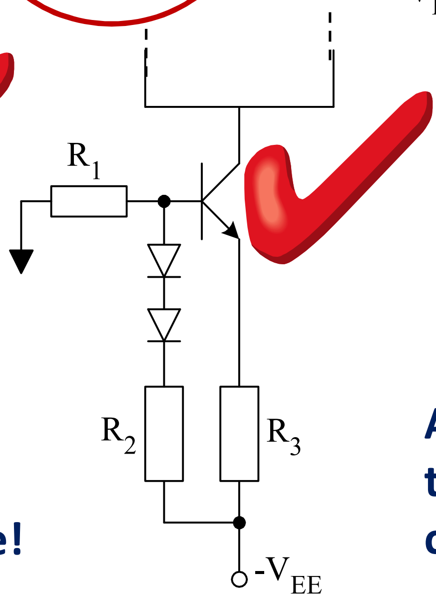


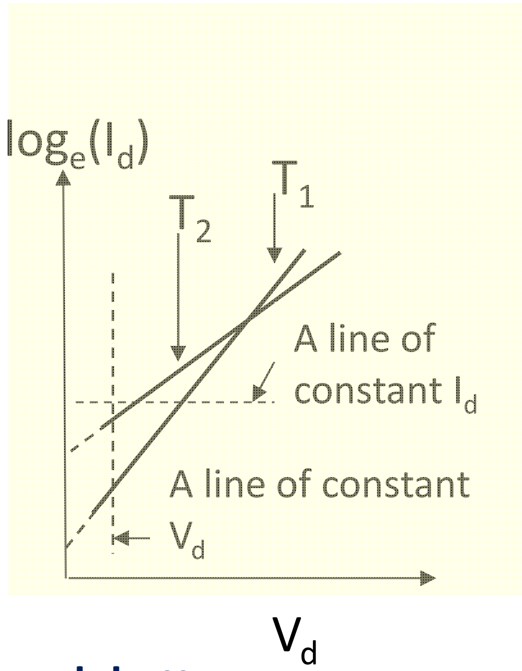
Symbols for a 'generic' current source

Already studied this one









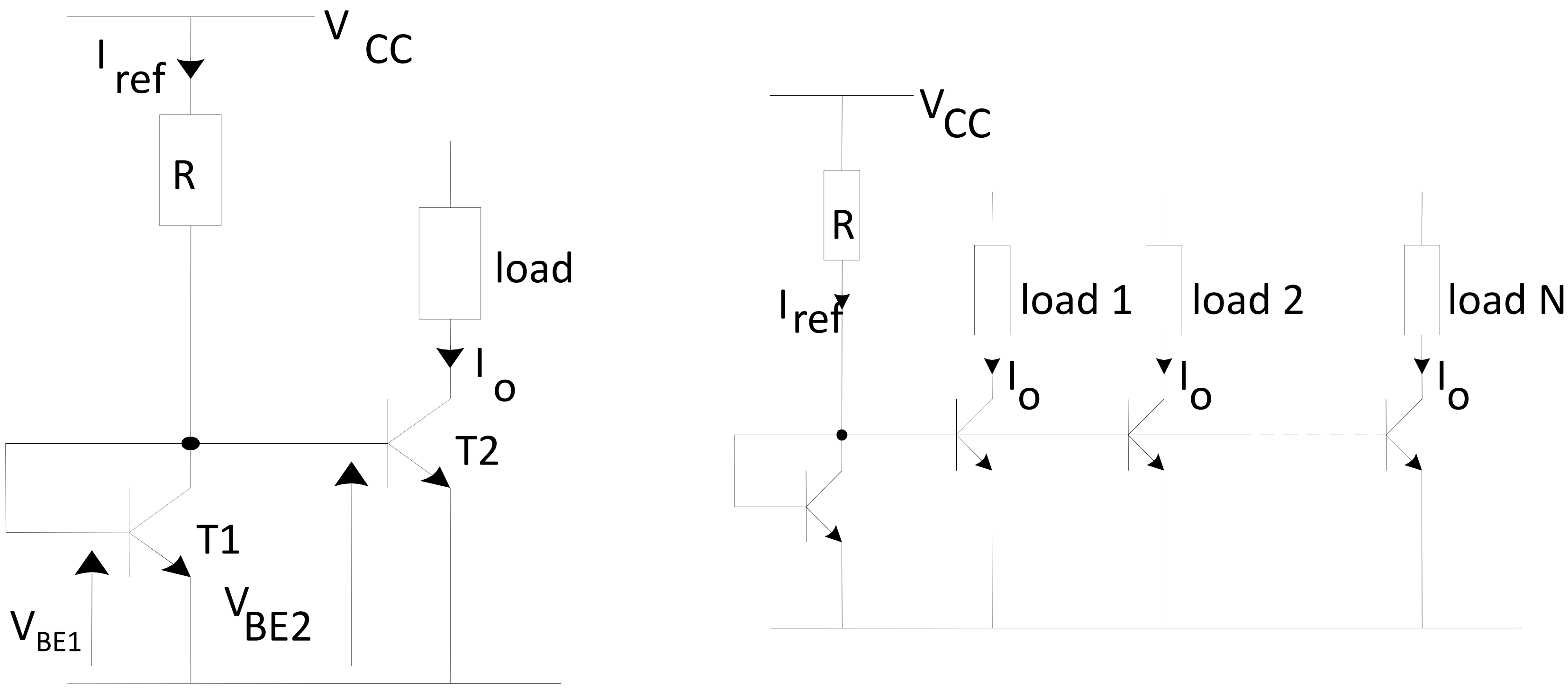
Simple current source formed by R_E and V_{EE}

A much better one!

A much better one that's temperature compensated!

Further biasing techniques

- Current mirrors and current repeaters



Next: The Widlar current mirror
– note that there are many other types of current source/mirrors

Widlar current mirror

Circuit analysis – DC: how to set I_o

$$V_{BE1} = V_{BE2} + I_o R_E$$

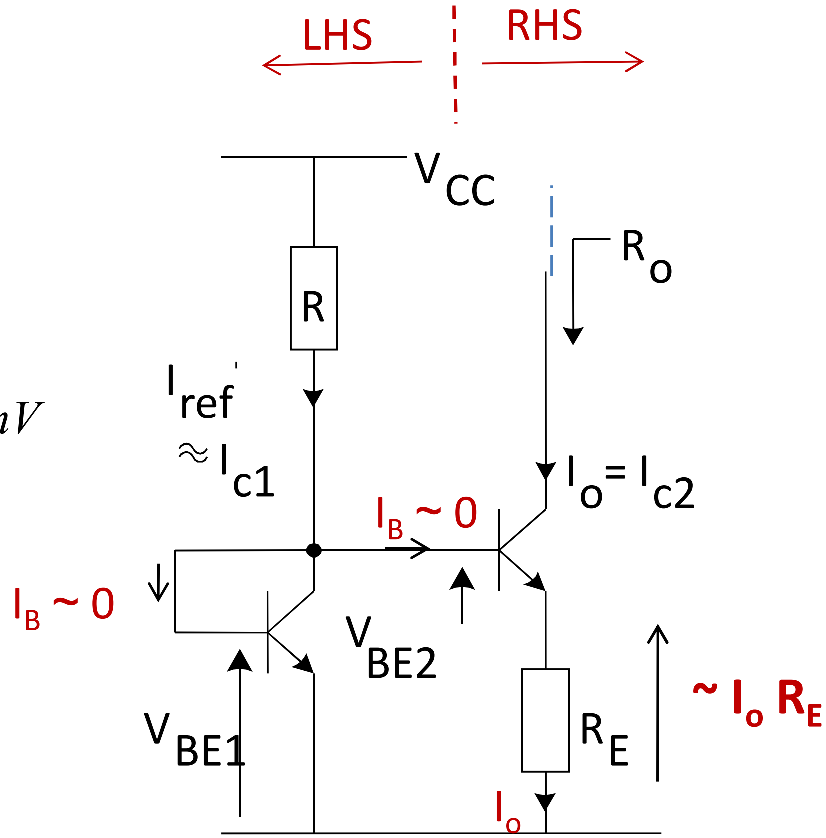
$$I_o R_E = V_{BE1} - V_{BE2}$$

$$I_{C1} = I_S \exp\left(\frac{V_{BE1}}{V_T}\right) \sim I_{ref} \qquad V_T = \frac{kT}{q} \sim 25mV$$

$$I_{C2} = I_S \exp\left(\frac{V_{BE2}}{V_T}\right) \sim I_o$$

hence

$$\begin{cases} V_{BE1} = V_T ln\left(\dfrac{I_{ref}}{I_S}\right) \\ V_{BE2} = V_T ln\left(\dfrac{I_O}{I_S}\right) \end{cases}$$



$$\boxed{I_O R_E = V_T ln\left(\frac{I_{ref}}{I_O}\right)}$$ **DESIGN EQUATION**

Set different currents in **current repeaters** by incorporating different R_E

Worked example

- Find **R, R_E** to give bias current **I_o = 0.1mA**. (assume V_{RE} ~ $4V_T$= 0.1V for stability).
- Given: V_{CC} = 5V, V_{EE} = -5V, transistors have current gains $\beta = \beta_o = 100$ and V_A = 150V.
- What will be the value of I_{ref}? Comment on your answer.

Solution

Widlar current mirror: $$I_O = \frac{V_T}{R_E} ln\left(\frac{I_{ref}}{I_O}\right) \quad ...(1)$$

For stability: set about $4V_T$ ~ 0.1V across R_E.

So try $$R_E = \frac{0.1}{1\times 10^{-4}} = 1k\Omega$$

Re-arrange (1) to get required value for I_{ref} .

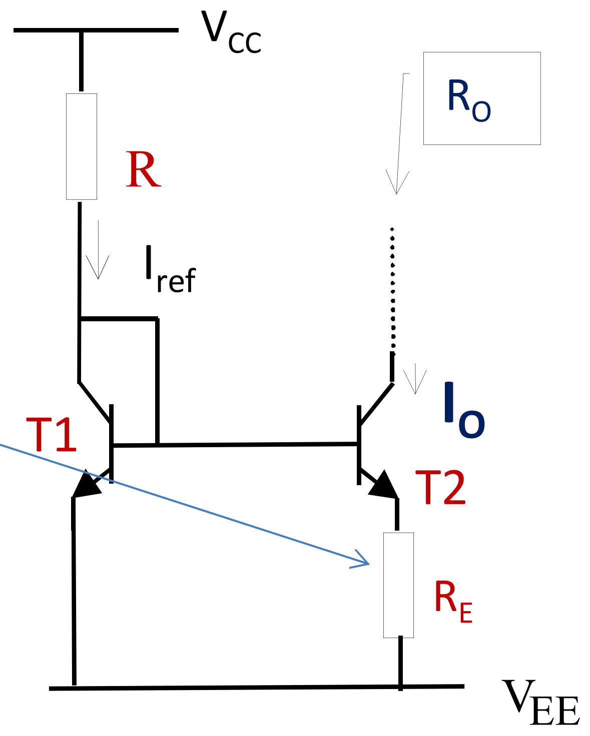
$$I_{ref} = I_o \exp\left[\frac{R_E I_o}{V_T}\right]$$

I_{ref} = 5.5mA

$$R = \frac{V_{CC} - (V_{EE}) - V_{BE}}{5.5\ mA}$$

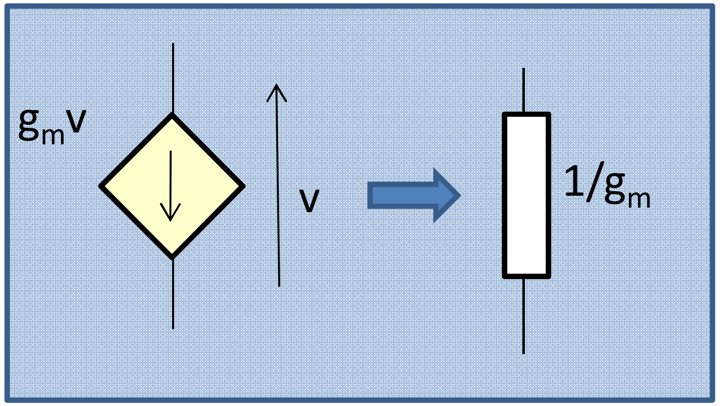
$$R = \frac{5-(-5)-0.7}{5.5\ mA} = \frac{10-0.7}{5.5\ mA} \approx 1.7\ k\Omega$$

R_E = 1 kΩ, R = 1.7 kΩ -small values!



And
g_{m1} = (40 × 5.5mA) = 220 mA/V,
g_{m2} = (40 × 0.1 mA) = 4 mA/V,
r_{ce2} = V_A/0.1mA = 150/0.1mA = 1.5MΩ

Note



A dependent current source of value $\mathbf{g_m v}$ with a voltage across it of value, **v** is equivalent to a resistance $\mathbf{1/g_m}$ by Ohm's Law.

$$v = i \times r$$

$$v = g_m v \times r$$

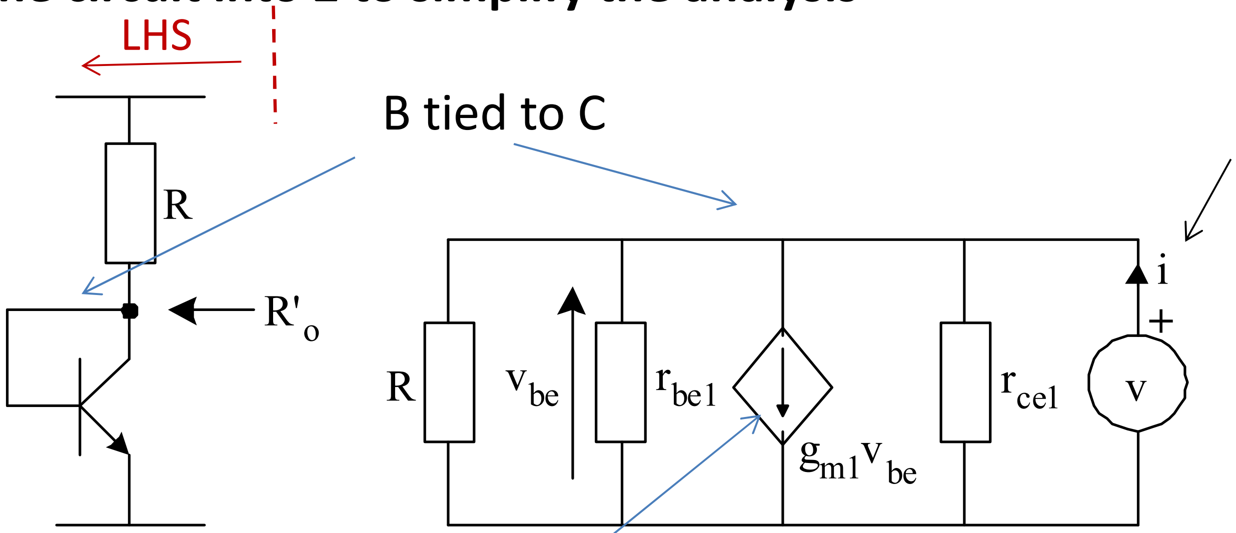
$$r = \frac{1}{g_m}$$

So can replace current source with a conductance, g_m

Or a resistance, r = 1/g_m

Now work out an expression for the **ac resistance, R_o** and hence find a numerical value for R_o.

- **Split the circuit into 2 to simplify the analysis**



Attach a test voltage , v and drive in a current, i

R_o' ~ v/i

By Ohm's Law

Note that the dependent current source, $g_{m1}v_{be1} = g_{m1}v$ as v_{be} = v!
- Write as $1/g_m$

so......

$$R_o' = R // r_{be1} // r_{ce1} // \frac{1}{g_{m1}} \approx \frac{1}{g_{m1}}$$

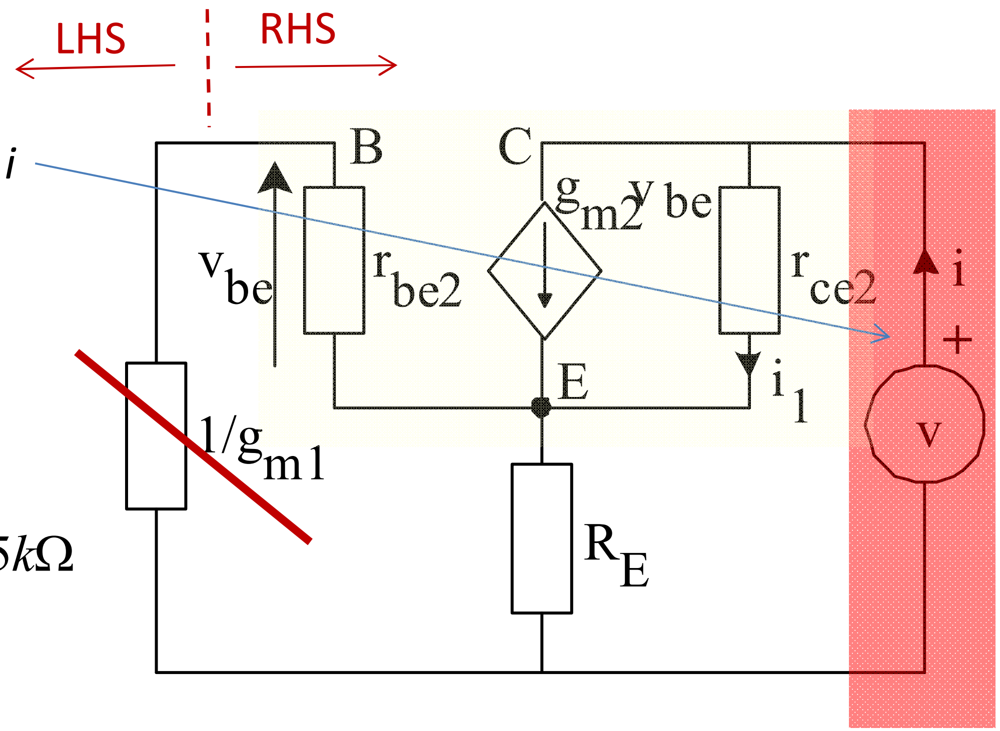
$\boxed{\mathbf{R = 1.7\ k\Omega}}$

Justify approximation: $g_{m1} = 40 \times I_{ref} = 40 \times 5.46mA \sim 218mA/V$

$$\boxed{\frac{1}{g_{m1}} = \frac{1}{218m} \sim 5\Omega}$$

$$r_{be1} \sim \frac{\beta_o}{g_{m1}} = \frac{100}{218 \times 10^{-3}} \sim 460\Omega \qquad r_{ce} \sim \frac{V_A}{I_{ref}} = \frac{150}{5.5 \times 10^{-3}} = 28k\Omega$$

Now find R_o



Apply a voltage source to force a current, *i* into the output of our current source.

The aim then is to find $R_o = v/i$

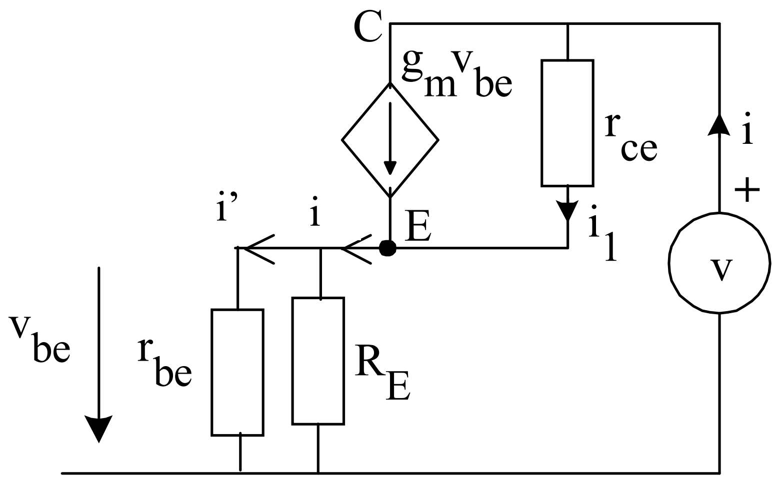
Can we make a further approximation?

$$r_{be2} = \frac{\beta_o}{g_{m2}} = \frac{100}{40 \times I_o} = \frac{100}{40 \times 0.1mA} = 25k\Omega$$

$1/g_{m1}$ ~ 5ohms and **So $r_{be2} >> 1/g_{m1}$!**

The schematic circuit is re-drawn.
We have managed to reduce the original circuit to quite a simple one.

drop the subscript '2' for simplicity.



Now find R_o

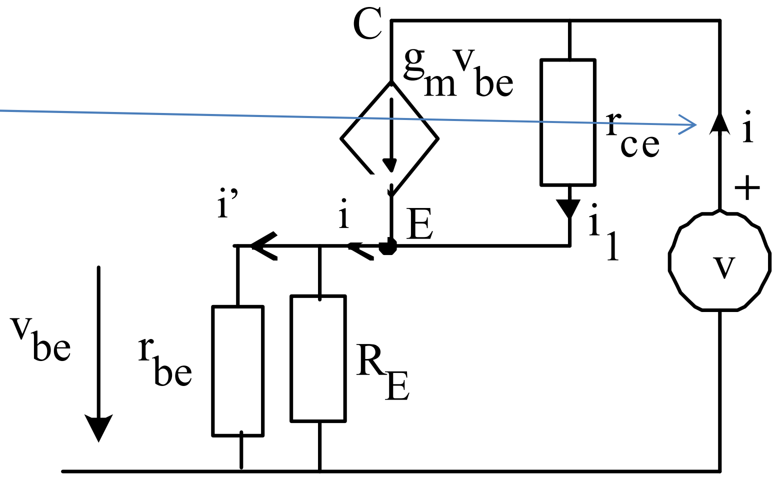
RHS

we can write

current through r_{ce}

$$i = g_m v_{be} + \frac{v-(-v_{be})}{r_{ce}} \quad (1)$$

$$i = \left(g_m + \frac{1}{r_{ce}}\right)v_{be} + \frac{v}{r_{ce}}$$



Need to find v_{be}: consider current division at 'E'

$$i' = i\frac{R_E}{r_{be}+R_E} = -\frac{v_{be}}{r_{be}}$$ **That is,** $v_{be} = -iR_E // r_{be}$

substitute $v_{be} = -iR_E // r_{be}$ into Eqn.1 to get: $i = -\left(g_m + \frac{1}{r_{ce}}\right)iR_E // r_{be} + \frac{v}{r_{ce}}$

$$R_O = \frac{v}{i} = r_{ce}\left[1+\left(g_m + \frac{1}{r_{ce}}\right)R_E // r_{be}\right]$$

...complicated expression!

But we can also say $g_{m2} >> 1/r_{ce2}$ (4m >> 0.1m/150~ 10^{-6}) giving $R_O \sim r_{ce}\left[1+\frac{R_E r_{be} g_m}{R_E + r_{be}}\right]$

Finally....

$$R_O \sim r_{ce}\left[1+\frac{R_E \times r_{be} \times g_m}{R_E + r_{be}}\right]$$

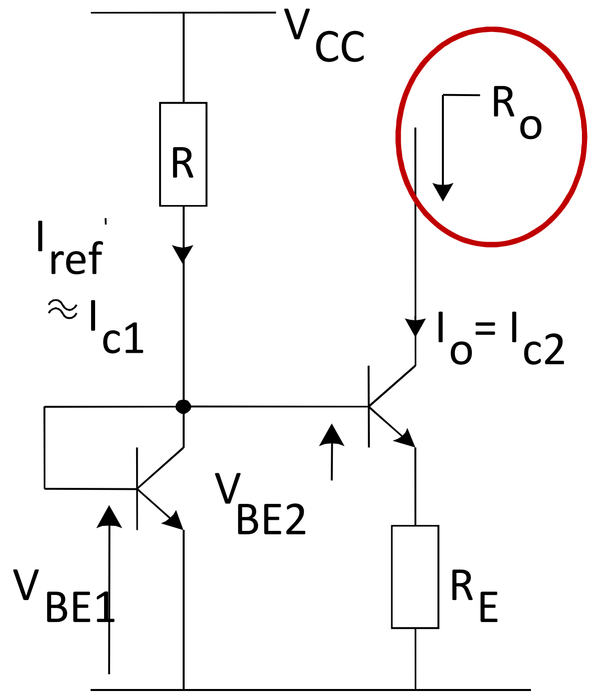
if $\mathbf{R_E} \ll \mathbf{r_{be2}}$ (1k < 25k)

OUTPUT RESISTANCE IS SIMPLY

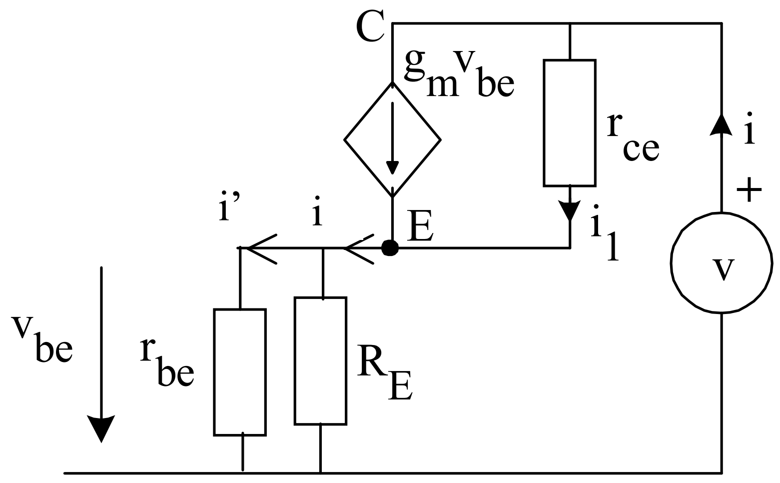
$$R_O \sim r_{ce}\left[1+g_m R_E\right]$$

Now $$g_m R_E = \frac{I_O}{V_T} R_E$$

and $R_E I_O$ is the voltage drop across R_E. !



We see therefore that we require at least a few **thermal volts** (25mV) across R_E to ‘multiply up’ the transistor output Resistance, r_{ce} to give a large R_o for our current source.



$$\boxed{R_O \sim r_{ce}\left[1+\frac{voltage\ \ drop\ \ across\ \ R_E}{25mV}\right]}$$

Example

$I_O = 0.1mA$, $R_E = 1k\Omega$

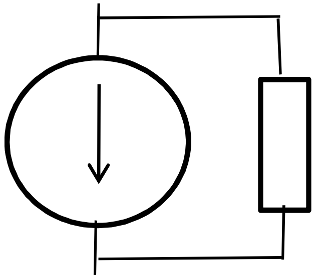
$$r_{ce} \sim \frac{V_A}{I_o} = \frac{150}{0.1mA}$$ **= 1.5MΩ**

$$R_O \sim r_{ce}[1 + g_m R_E]$$
$$= 1.5M[1 + 40 \times 0.1m \times 1000]$$

$$R_O \sim r_{ce}[1 + 4]$$ **R_o = 7.5MΩ**

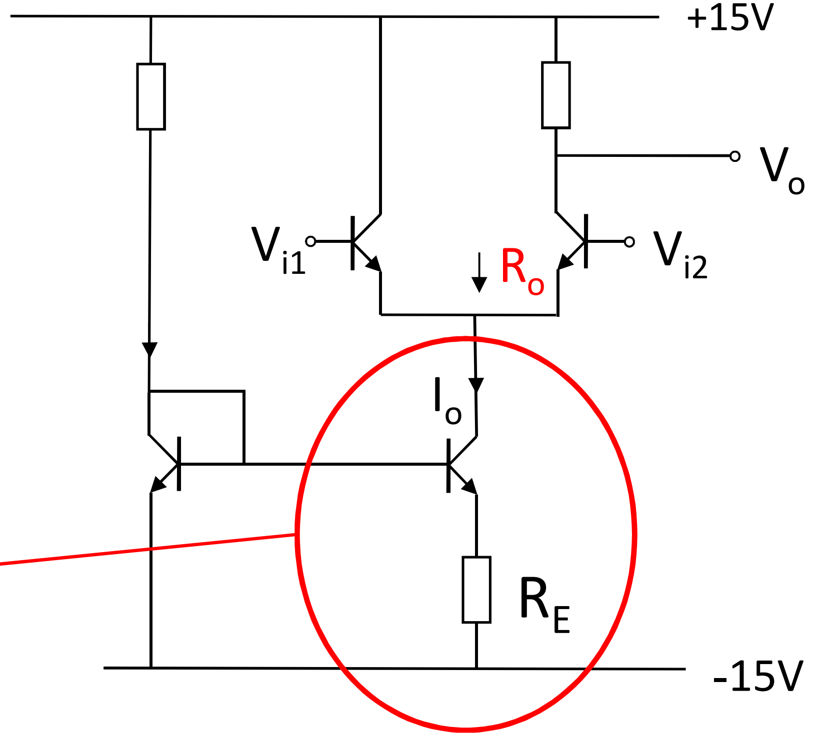
I_o = 0.1mA

DC part



R_o ~ 7.5MΩ

AC part

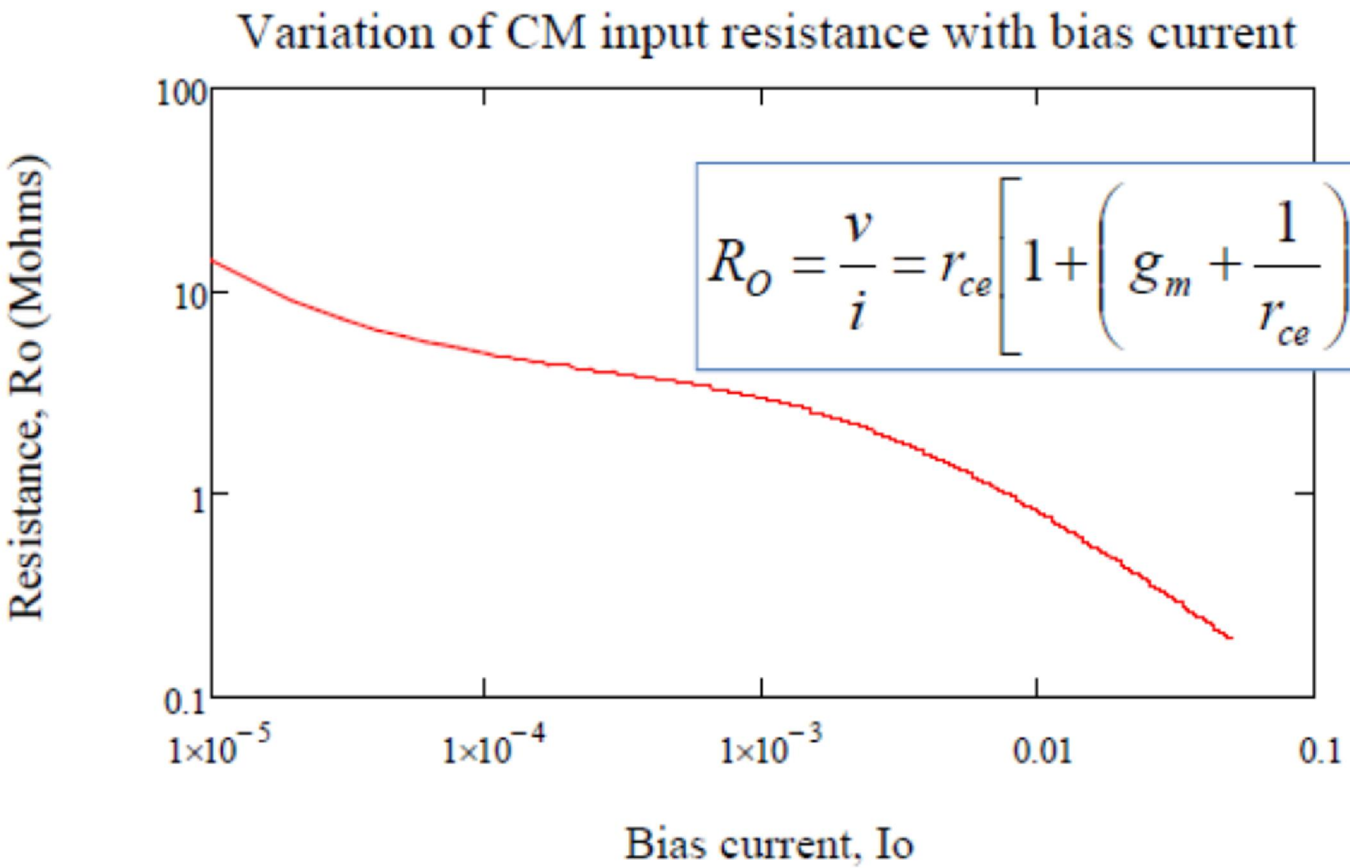


An example of the use of a Widlar current mirror to provide the bias current, I_o for a differential amplifier

And simple estimate of CMRR is

$$CMRR \sim \frac{R_o I_O / 2}{25m} = 15{,}000$$

R_o stays quite large as bias current increases



$$R_O = \frac{v}{i} = r_{ce}\left[1 + \left(g_m + \frac{1}{r_{ce}}\right) R_E \,//\, r_{be}\right]$$

$$g_m = \frac{I_O}{25m}$$

$$r_{ce} \sim \frac{V_A}{I_o}$$

$$r_{be} = \frac{\beta_o}{I_o} \times 25mV$$

- Large R_o gives small common-mode gain
- Large I_o gives high differential-mode gain
- Overall, large common-mode rejection ratio with Widlar current source

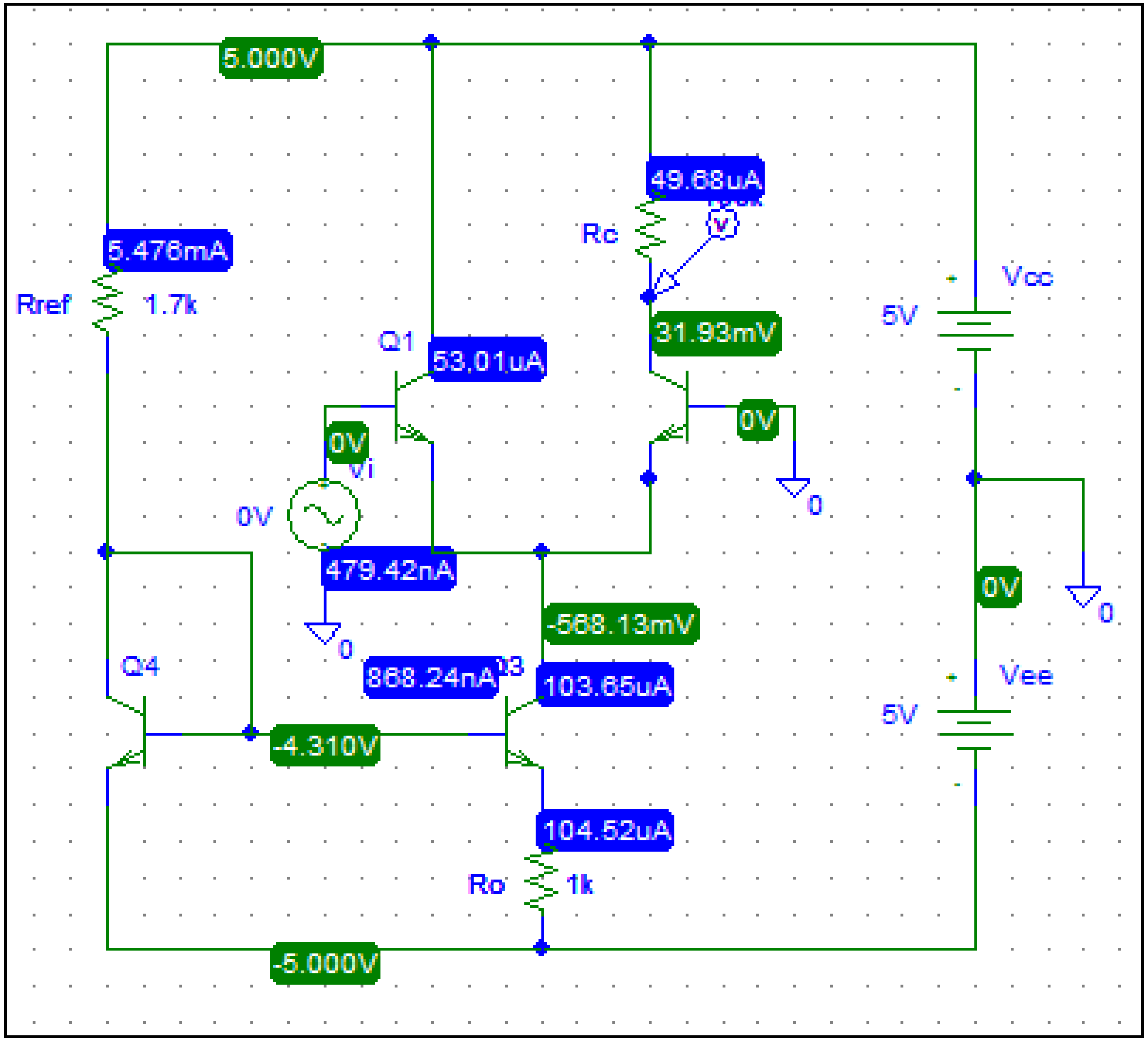
PSPICE DC simulation: V and I

I_{ref} = 5.5 mA
Sim: 5.48 mA

I_o = 100 mA
Sim: 104 mA

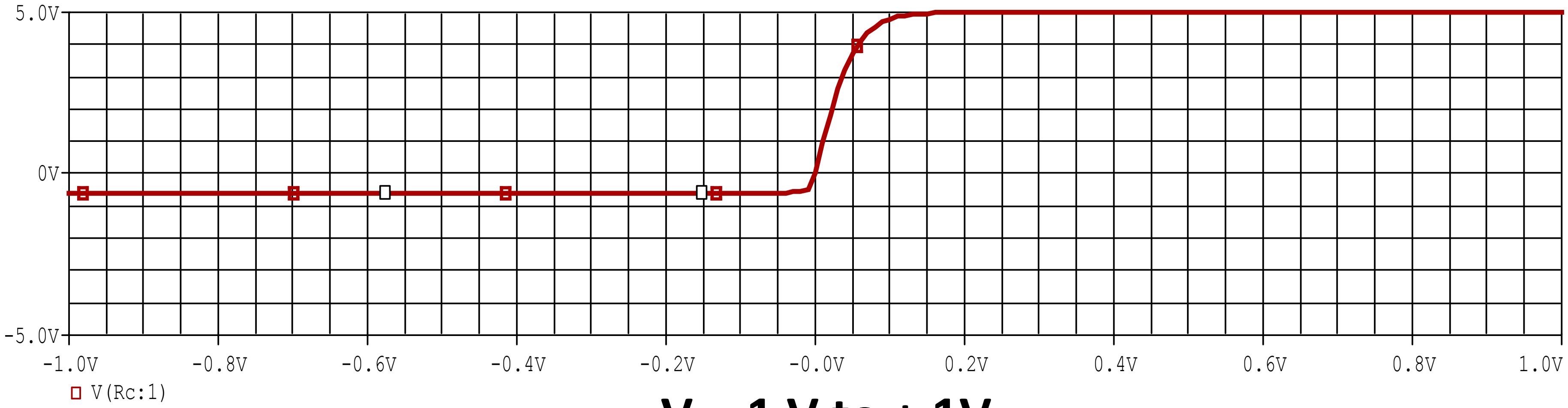
V_{out} = 0 V
Sim: 32 mV

Agreement quite good



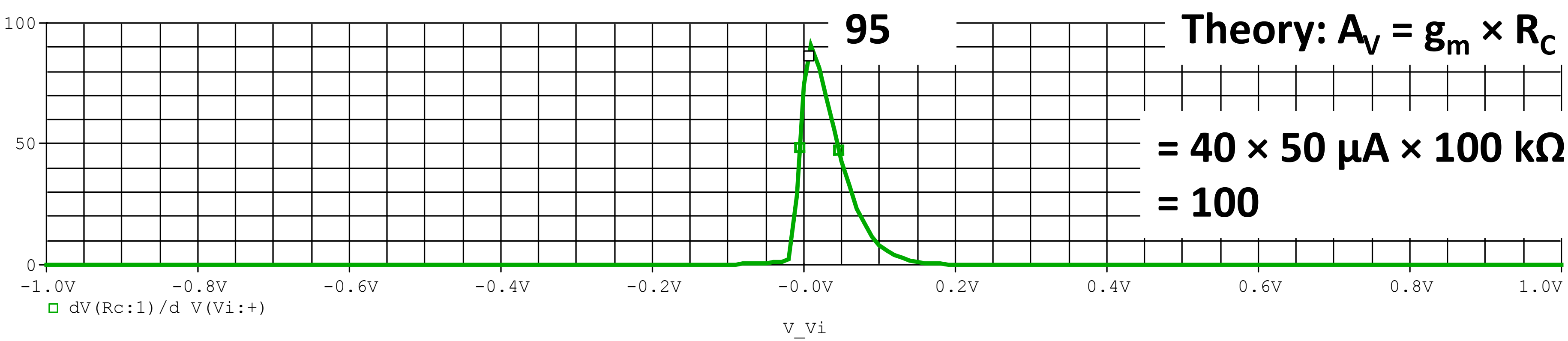
DC Sweep: Diff. gain

V_{OUT} : -5 V to + 5 V



V_i: -1 V to + 1V

A_V

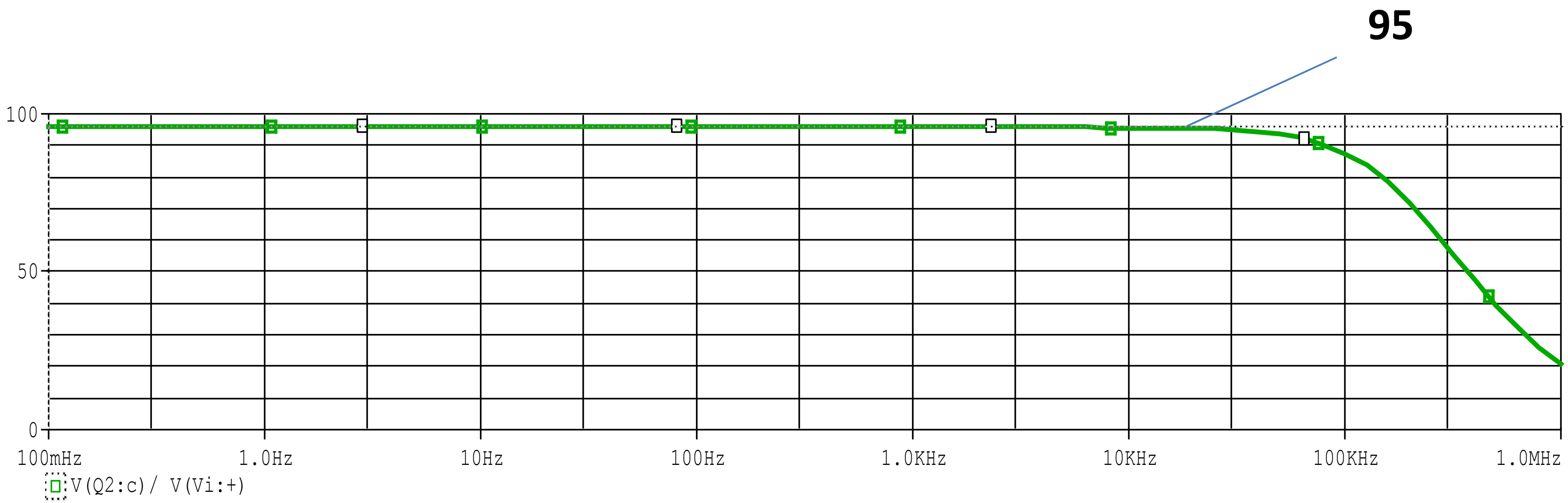


Theory: $A_V = g_m \times R_C$

$= 40 \times 50\ \mu A \times 100\ k\Omega$

$= 100$

AC Sweep: Voltage gain



Frequency: 0.1 Hz to1 MHz

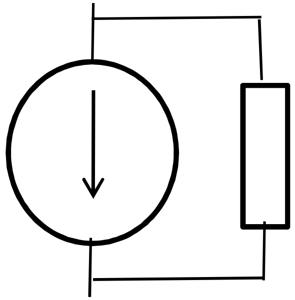
Note: Gain down to DC!

No coupling capacitors

Ro value

$$R_O \sim r_{ce}\left[1 + g_m R_E\right]$$

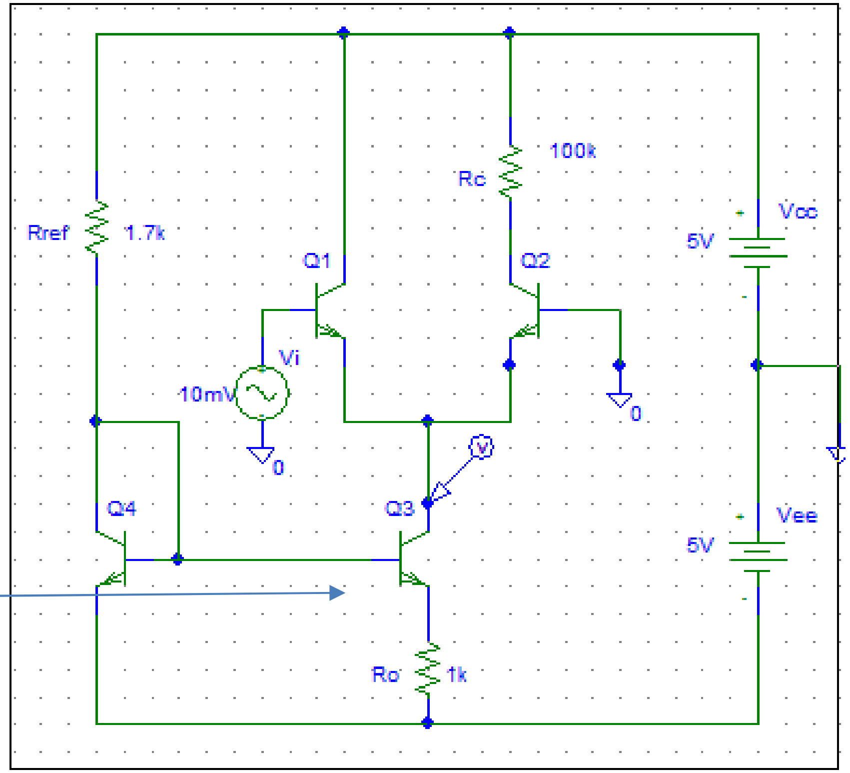
I_o = 0.1mA



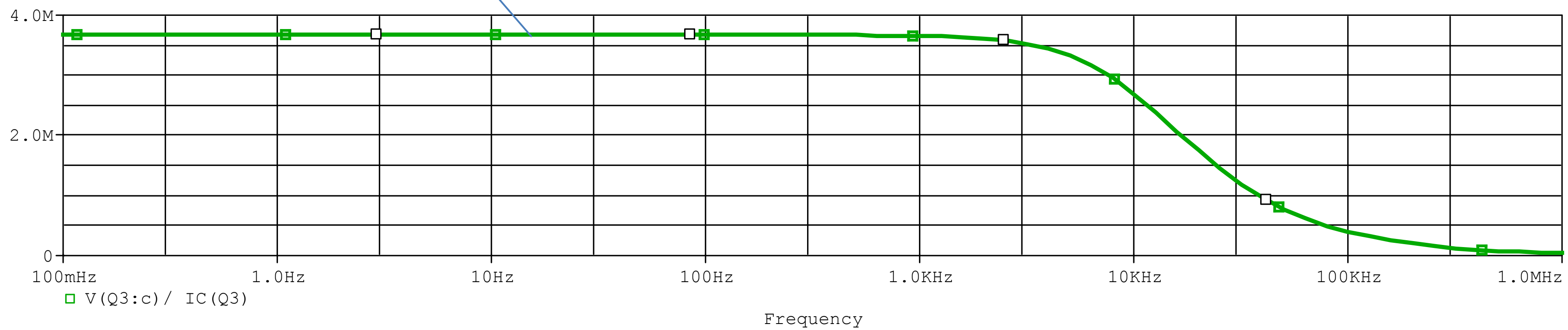
R_o ~ 7.5 MΩ

Using Early voltage of 150 V

R_o = 3.7 MΩ using V_A = 74 V(2N2222)

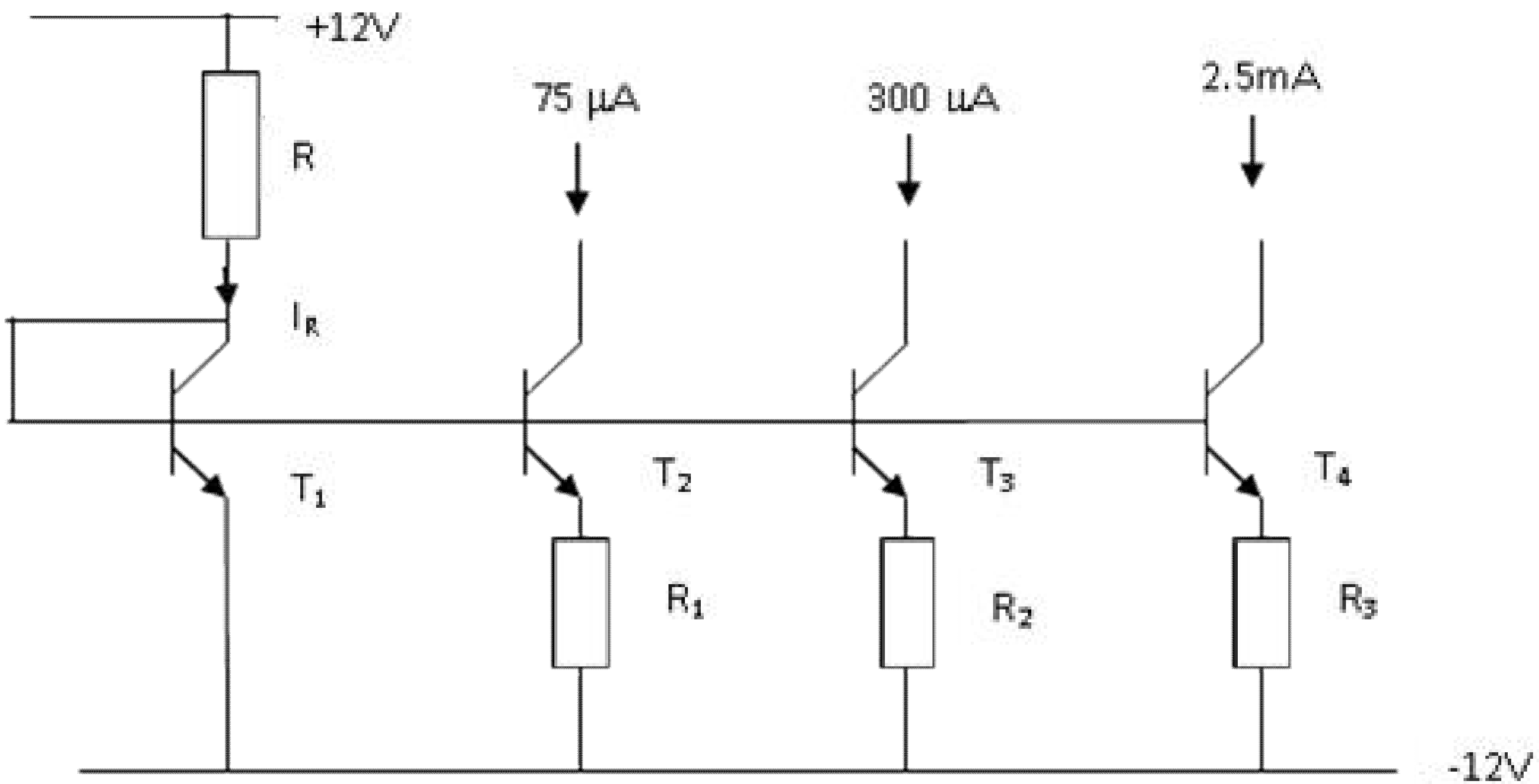


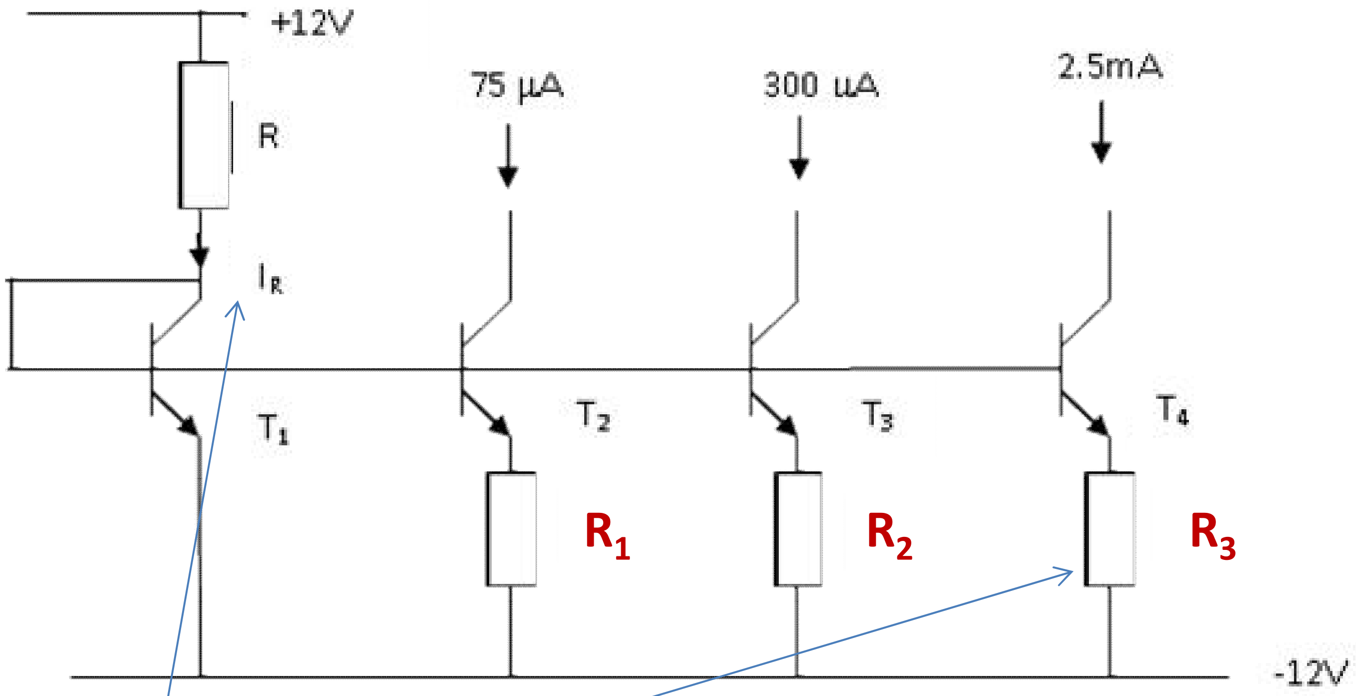
3.7 MΩ



Worked Example

An operational amplifier comprises three stages with bias requirements of 75 µA, 300 µA and 2.5 mA. Sketch the circuit and design the current mirror arrangement to provide these bias currents. Assume power supplies of +/- 12V, identical transistors with Early voltages, V_A = 100 V, V_T =25 mV and V_{BE} = 0.7V. Take $r_{ce} = V_A/I_C$.



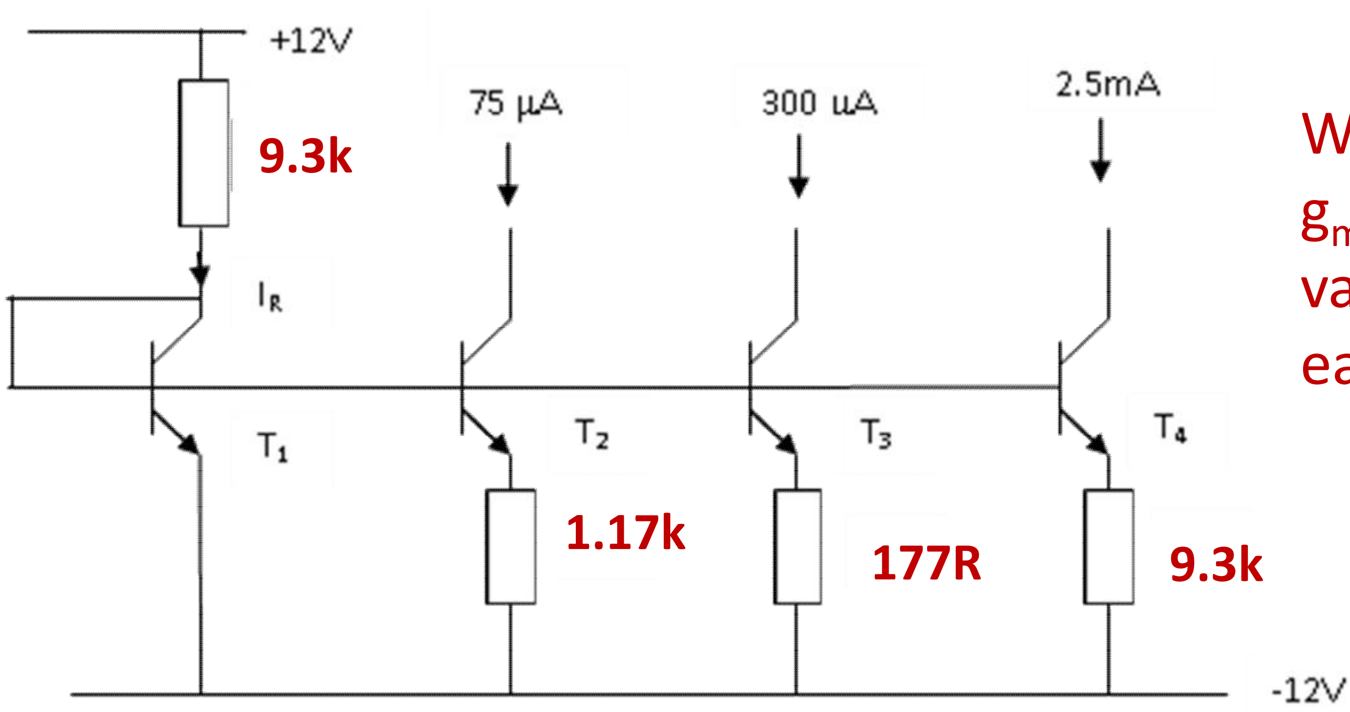


Choose I_R = 2.5mA then R_3 = 0 (simple current mirror)

$$R = \frac{V_{CC} - (-V_{EE} + V_{BE})}{I_R} = \frac{V_{CC} + |V_{EE}| - V_{BE})}{I_R} = \frac{24 - 0.7}{2.5 \times 10^{-3}} = 9.3k\Omega$$

$$R_1 = \frac{V_T}{I_{O1}} ln\left(\frac{I_R}{I_{O1}}\right) = \frac{2.5 \times 10^{-3}}{75 \times 10^{-6}} ln\left(\frac{2.5mA}{75\mu A}\right) = 1.17k\Omega$$

$$R_2 = \frac{V_T}{I_{O2}} ln\left(\frac{I_R}{I_{O2}}\right) = \frac{2.5 \times 10^{-3}}{300 \times 10^{-6}} ln\left(\frac{2.5mA}{300\mu A}\right) = 177\Omega$$



Work out g_m and r_{ce} values for each transistor

$$R_{o2} \sim r_{ce2}\left[1 + g_{m2} \times R_1\right] = 1.3 \times 10^6 \left[1 + 3 \times 10^{-3} \times 1.17 \times 10^3\right] = 5.86M\Omega$$

$$R_{o3} \sim r_{ce3}\left[1 + g_{m3} \times R_2\right] = 333 \times 10^3 \left[1 + 12 \times 10^{-3} \times 177\right] = 1.04M\Omega$$

$$R_{o4} \sim r_{ce4}\left[1 + g_{m4} \times 0\right] = 40 \times 10^3 = 40k\Omega$$

MCQ

Current sources are used for the following purpose:

a) Provide more gain
b) To provide the DC bias for circuits
c) Reduce power consumption
d) Increase amplifier output resistance

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For the differential amplifier, use of a current source has the benefit of:

a) Increasing the differential gain
b) Increasing the common-mode gain
c) Decreasing the common-mode rejection ratio
d) Increasing the common-mode rejection ratio

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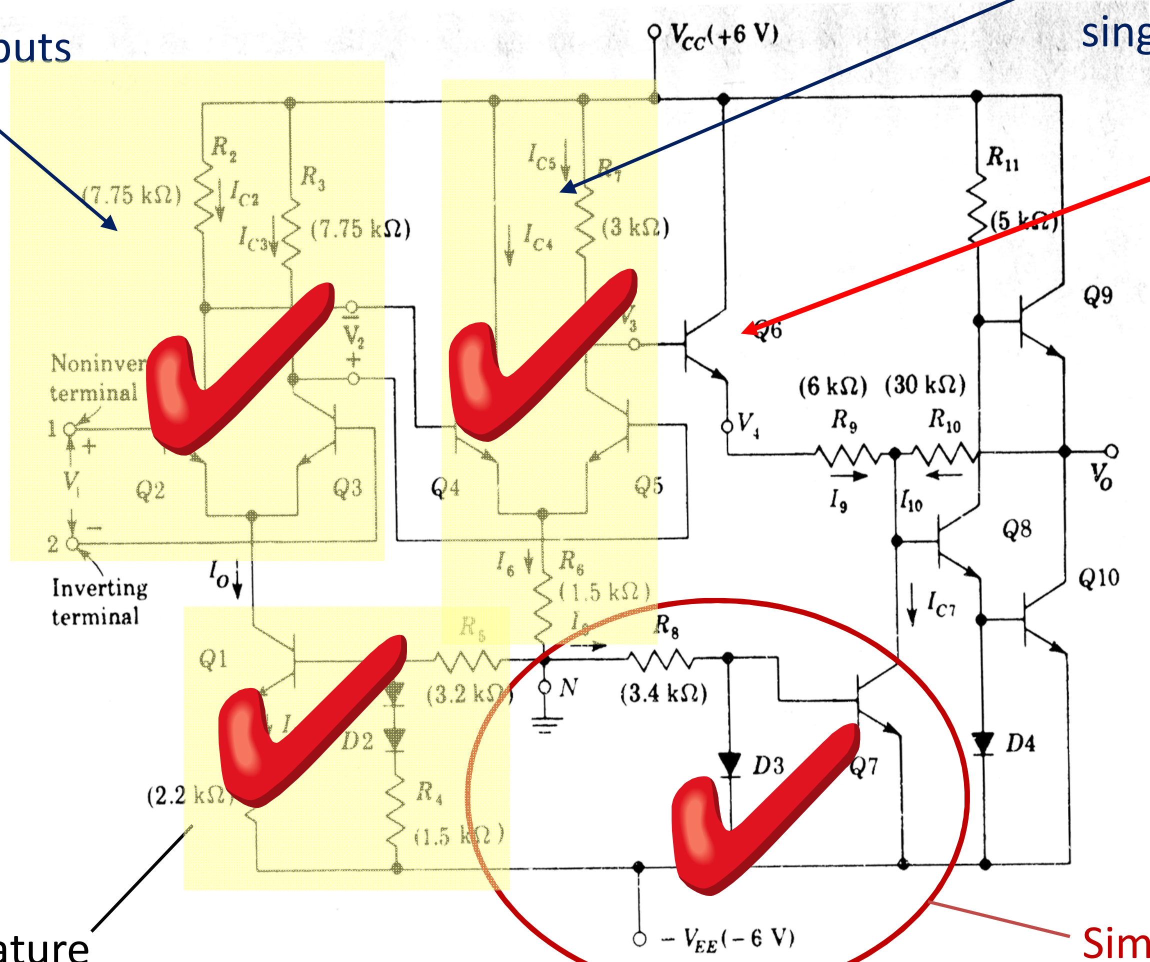
Milestone...

Differential amplifier
Two outputs

Differential amplifier
single output

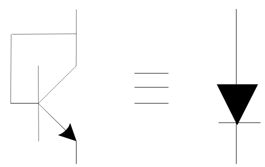
Signal goes into base, comes out of emitter ??????



Temperature compensated current source

Simple current mirror

- Identify building blocks
- Perform a d.c. analysis
- Perform an a.c. analysis

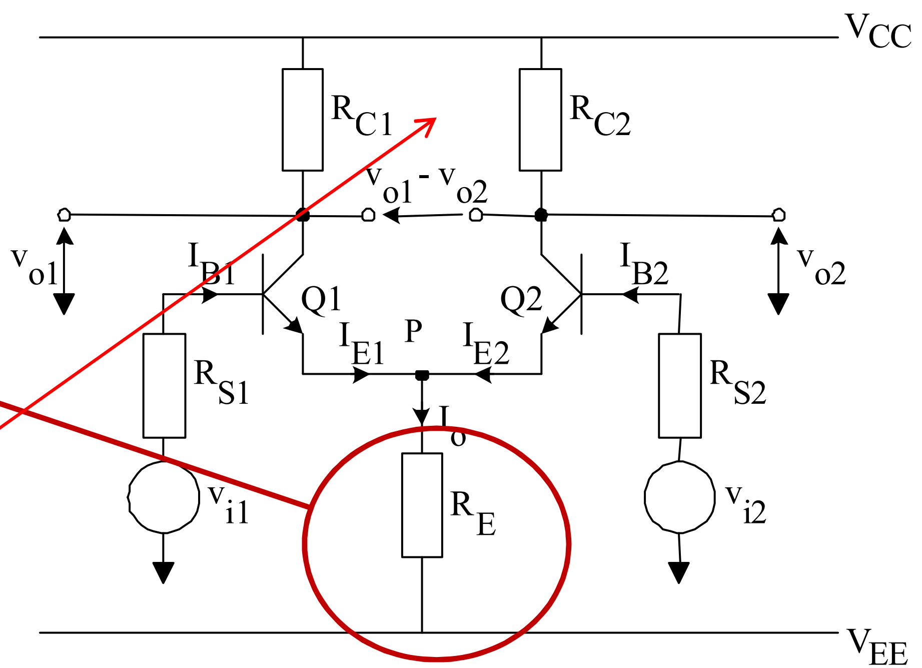


Next lecture

Recall the ‘problems’ with the Diff Amp

We require

- **a better bias circuit to replace R_E, which will allow us to… t the current I_o, indepe…ently o… e resistance in the ‘t…**
- **We w… so like such a bias circuit to exhibit a very large dynamic resistance to give high common mode rejection ratio (CMRR).**



ACTIVE LOADS:

replace the collector resistors to give a high resistance (for high gain)