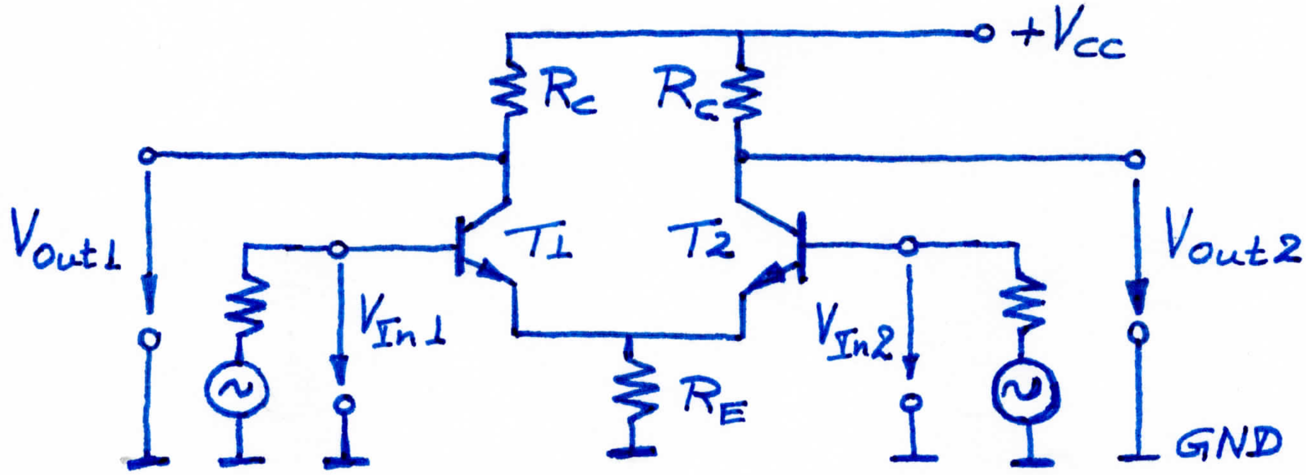
Iconic circuit: Differential amplifier

* Differential amplifier is physical basis of Operational Amplifier (Op Amp).
* Two inputs. Two outputs.
* Amplifies differece in input voltages.

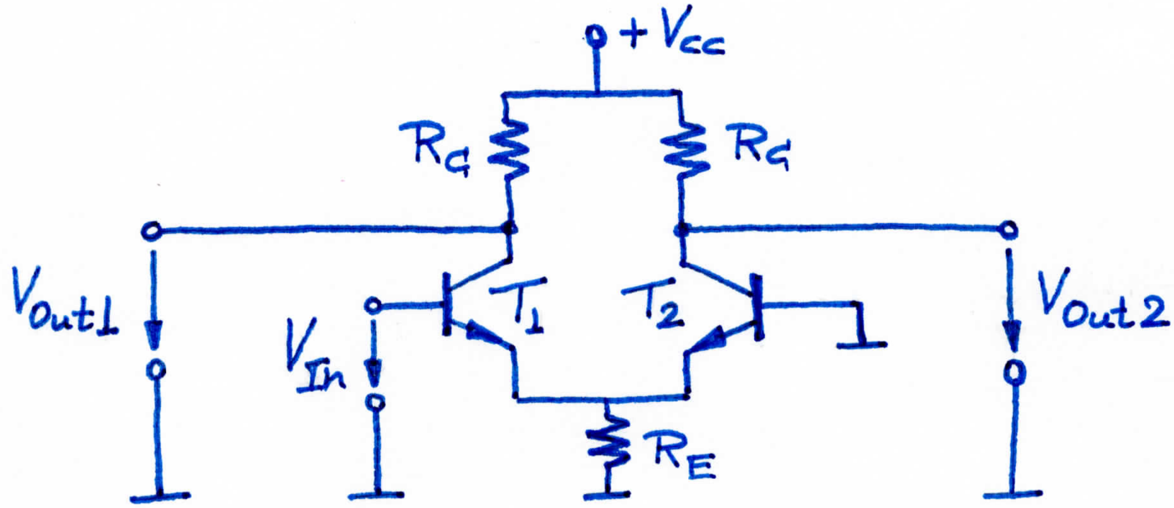


* Emitters are coupled and share R_E.
* 1 or 2 inputs (unused input can be grounded)
* 1 or 2 outputs (unused output can be floating)
* Two modes of operation

Common mode: $V_{In1} = V_{In2}$

Differential mode: $\underbrace{V_{In1} \neq V_{In2}}$ → Difference $\neq 0$

Inverting output and non-inverting output



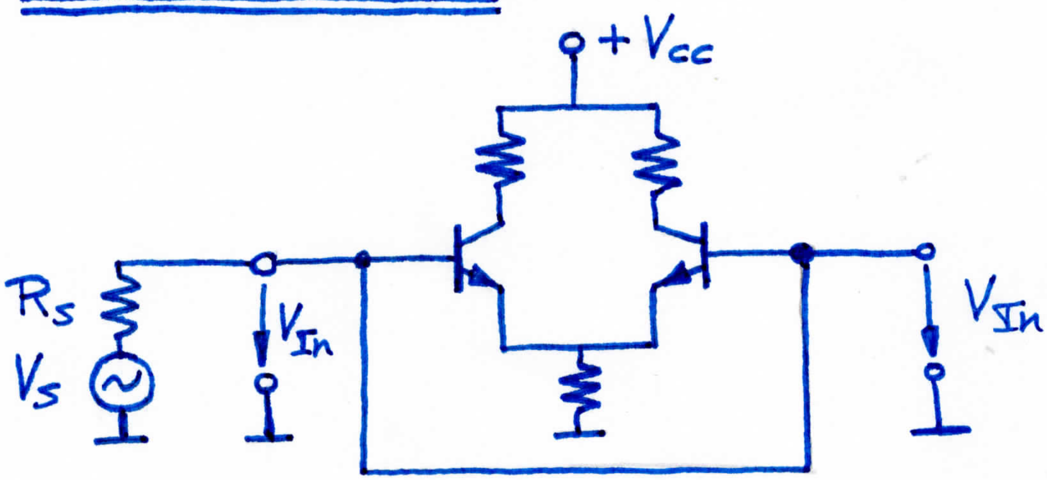
Q: Which output is inverting output?

⇒ Output 1 is inverting.

Q: Which output is non-inverting output

⇒ Output 2 is non-inverting.

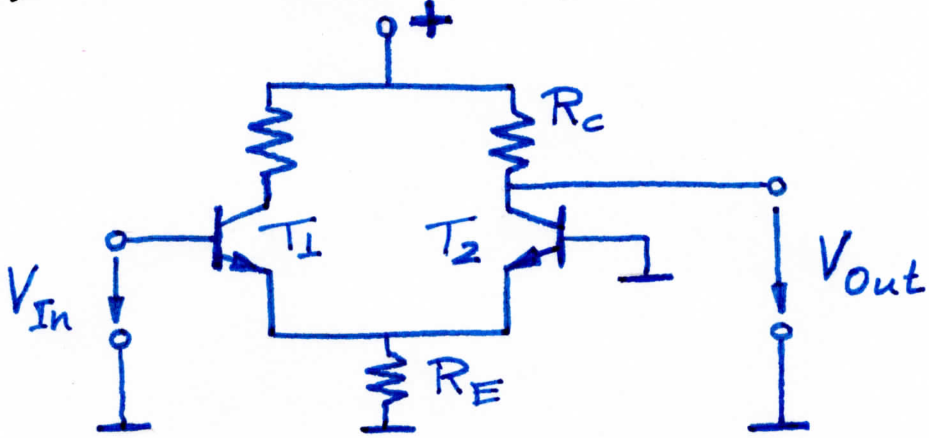
Common mode (CM): Both inputs at same voltage



$$\Rightarrow \quad V_{In1} = V_{In2} = V_{In}$$

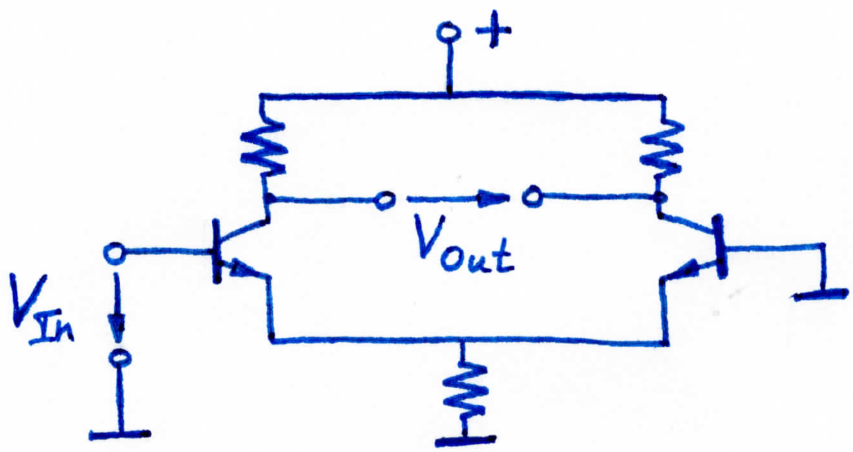
Input and output configurations

* Single input & single output



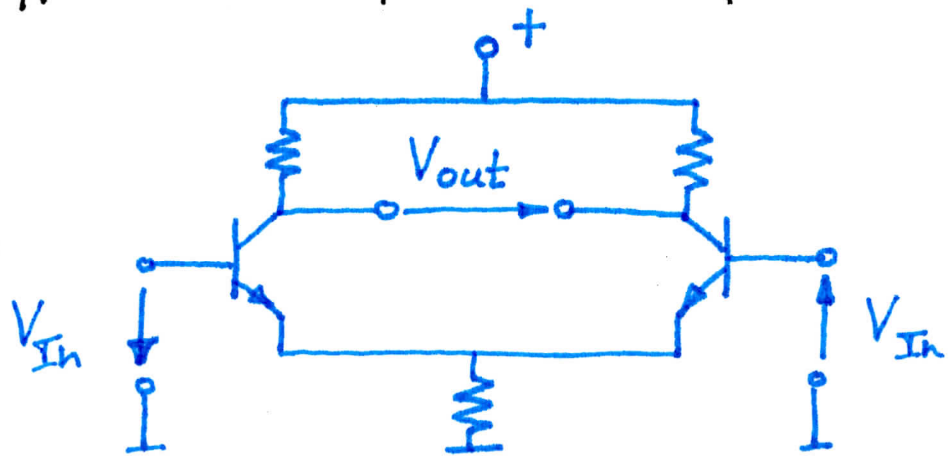
⇒ To be shown: $A = R_C / 2r_E$

* Single input & differential output



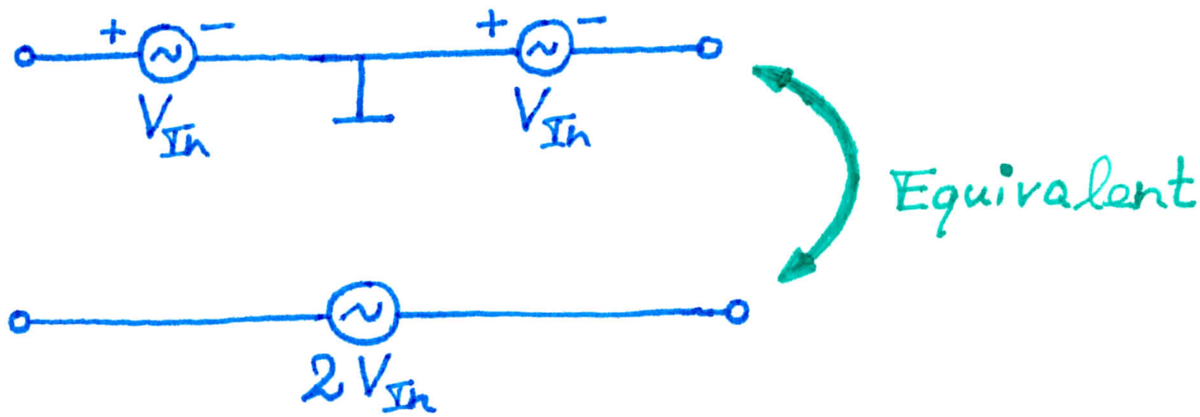
⇒ To be shown: $A = R_C / r_E$

* Differential input & differential output

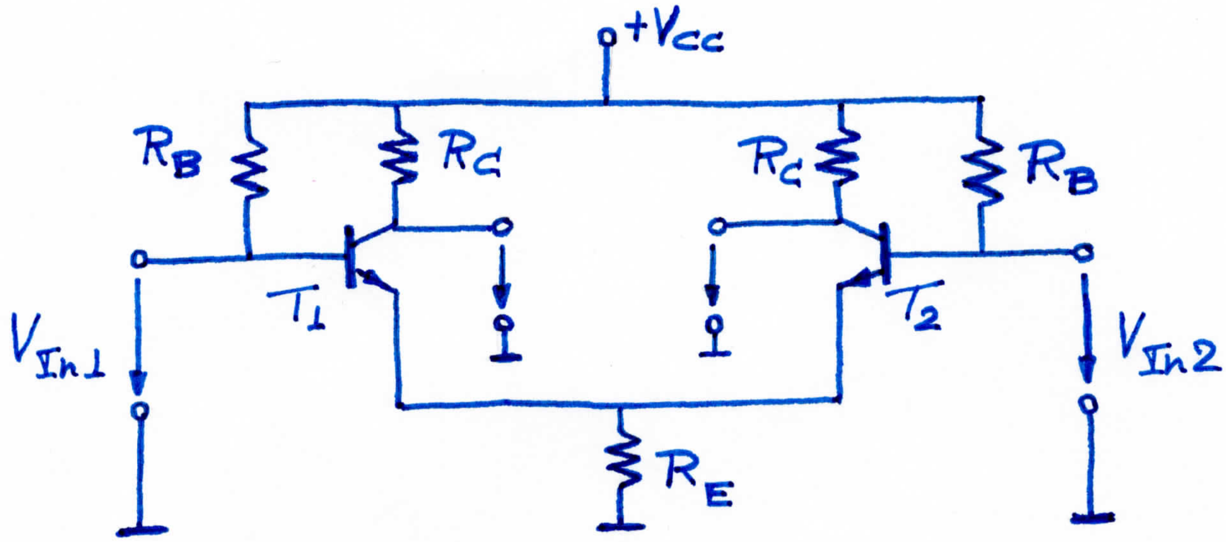


⇒ To be shown: $A = \frac{2R_c}{r_E}$

Note on input voltage representation



Quiescent point (Q-point)



⇒ Symmetric circuit

⇒ Q-point: $I_{B1} R_B + V_{BE} + 2(\beta+1) I_{B1} R_E = V_{CC}$

$$\Rightarrow I_{B1} = \frac{V_{CC} - 0.7V}{R_B + 2(\beta+1) R_E}$$

$$\Rightarrow I_{E1} = (\beta+1) I_{B1} \qquad I_{C1} = \beta I_{B1}$$

$$\Rightarrow V_E = 2 I_{B1} (\beta+1) R_E$$

$$V_C = V_{CC} - \beta I_{B1} R_C$$

$$\Rightarrow V_{CE} = V_C - V_E = V_{CC} - \beta I_{B1} R_C - 2 I_{B1} (\beta+1) R_E$$

$$\approx V_{CC} - \beta I_{B1} (R_C + 2 R_E)$$

... this concludes our Q-point calculation.

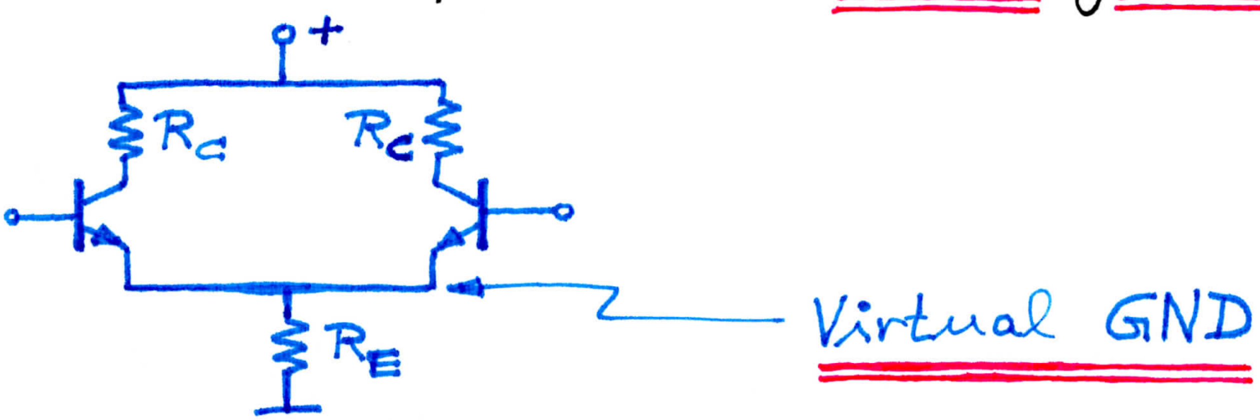
Q: What would be a good value of V_{CE}?

Qualitative discussion

* Common mode : $V_{In1} = V_{In2} \Rightarrow$ Due to symmetry of circuit $I_{C1} = I_{C2} \Rightarrow V_{out} = 0$
$\Rightarrow A_{CM} = 0$

* Differential mode : Assume $V_{In1} \uparrow \Rightarrow$
$\Rightarrow V_{BE1} \uparrow$ and $V_E \uparrow \Rightarrow V_{BE2} \downarrow \Rightarrow$
(V_{BE1} → ~ 0.7V; V_{BE2} → ~ 0.7V)
$\Rightarrow I_{E1} \uparrow$ and $I_{E2} \downarrow \Rightarrow I_{C1} \uparrow$ and $I_{C2} \downarrow$
$\Delta I_{C1} = \Delta I_{C2}$ due to linearization of circuit.
$\Rightarrow$ Current is "**steered**" through T_1 & T_2

* $I_{RE} = I_{E1} + I_{E2}$. Since $I_{E1} \uparrow$ and $I_{E2} \downarrow$ (by same amount) $\Rightarrow I_{RE} =$ constant $\Rightarrow$
$V_{RE} =$ constant $\Rightarrow V_E =$ constant $\Rightarrow$ Emitters are at constant potential $\Rightarrow$ "virtual ground"



Amplification

$$A_{CM} = \frac{V_{out}}{\frac{1}{2}(V_{in1} + V_{in2})} = 0$$ (already shown)

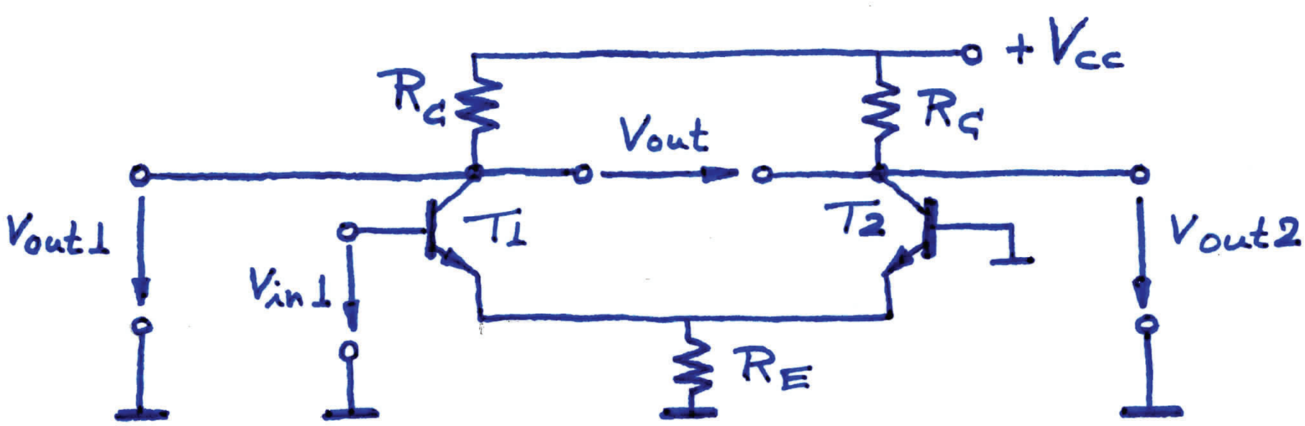
Single input & single output $\quad A = \frac{V_{out1}}{V_{in1}} = ?$

Single input & differential output $\quad A = \frac{V_{out1} - V_{out2}}{V_{in1}} = ?$

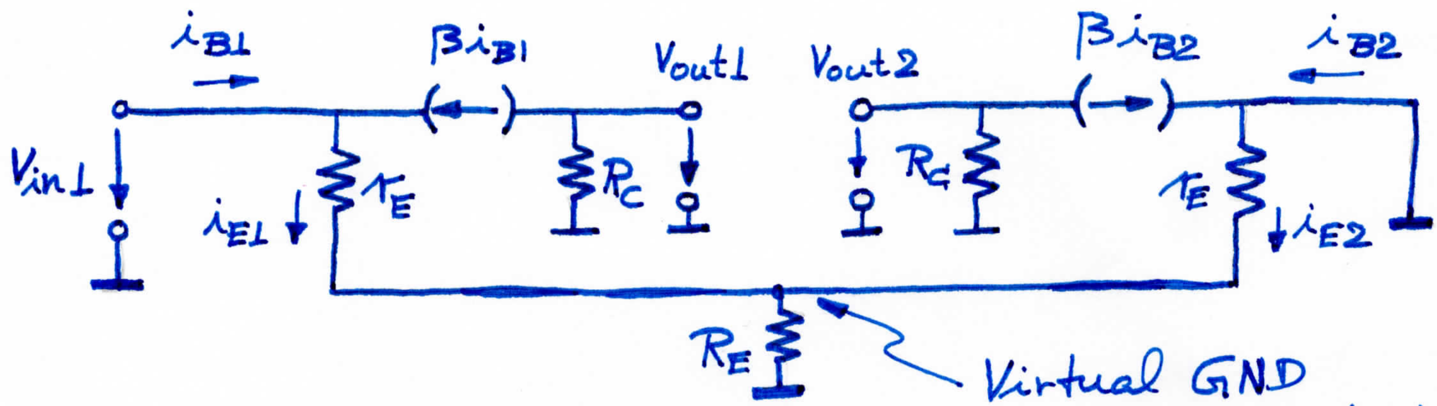
Differential input & output $\quad A = \frac{V_{out1} - V_{out2}}{V_{in}} = ?$

Next, we consider single input & differential output

⇒ Circuit diagram



Small-signal equivalent circuit



⇒ constant potential
⇒ V_{RE} = constant
⇒ No small-signal current through R_E

$$V_{out1} = \beta\, i_{B1}\, R_C$$

$$V_{out2} = \beta\, i_{B2}\, R_C$$

$$V_{in1} = i_{E1}\, r_E + \underbrace{i_{E1}}_{= -i_{E2}}\, r_E = 2\, i_{E1}\, r_E$$

$$A = \frac{V_{out1} - V_{out2}}{V_{in1}} = \frac{\beta\, i_{B1} R_C - \beta\, \overbrace{i_{B2}}^{= -i_{B1}} R_C}{2\, i_{E1}\, r_E}$$

$$= \frac{2\beta\, i_{B1} R_C}{2(\beta+1)\, i_{B1}\, r_E} \approx \frac{R_C}{r_E}$$

* Single input & single output: $A = \dfrac{R_C}{2 r_E}$ Why?

* Differential input & output: $A = \dfrac{2 R_C}{r_E}$ Why?

Summary table

Input	Output	Gain
single	single	$R_C/2r_E$
single	differential	R_C/r_E
differential	differential	$2R_C/r_E$

Example: Consider a differential amplifier with differential input & output. $V_{CC} = 12\,V$. Assume $R_C = 500\,\Omega$ and $I_{C1} = 10\,mA$.

* Determine the voltage gain. $I_{E1} \approx I_{C1} = 10\,mA$

$$\Rightarrow r_E = \frac{V_t}{I_{E1}} = \frac{26\,mV}{10\,mA} = 2.6\,\Omega$$

$$\Rightarrow A = \frac{2R_C}{r_E} = \frac{1000\,\Omega}{2.6\,\Omega} = \underline{\underline{384}}$$

* What is the gain of a 2-stage amplifier?

$$\Rightarrow A = A_{1st\text{-}stage} \times A_{2nd\text{-}stage} = 384 \times 384 = \underline{\underline{148\,000}}$$

$\Rightarrow$ Reasonable value for Op Amp.

Applications

* Operational amplifier. The basic internal circuit of an Op Amp is a 2-transistor differential amplifier. Amplification of Op Amp $\approx$ 100,000. Amplification of differential amplifier $\approx$ 200. $\Rightarrow$ Multiple stages needed.

* Emitter-coupled logic (ECL). Also called current steering logic (CSL). ECL is very fast. But: Power consumption is high. ECL consumes power at the quiescent point (Q-point).