Imperial College London

Lecture 3

The Anatomy of an Op-Amp

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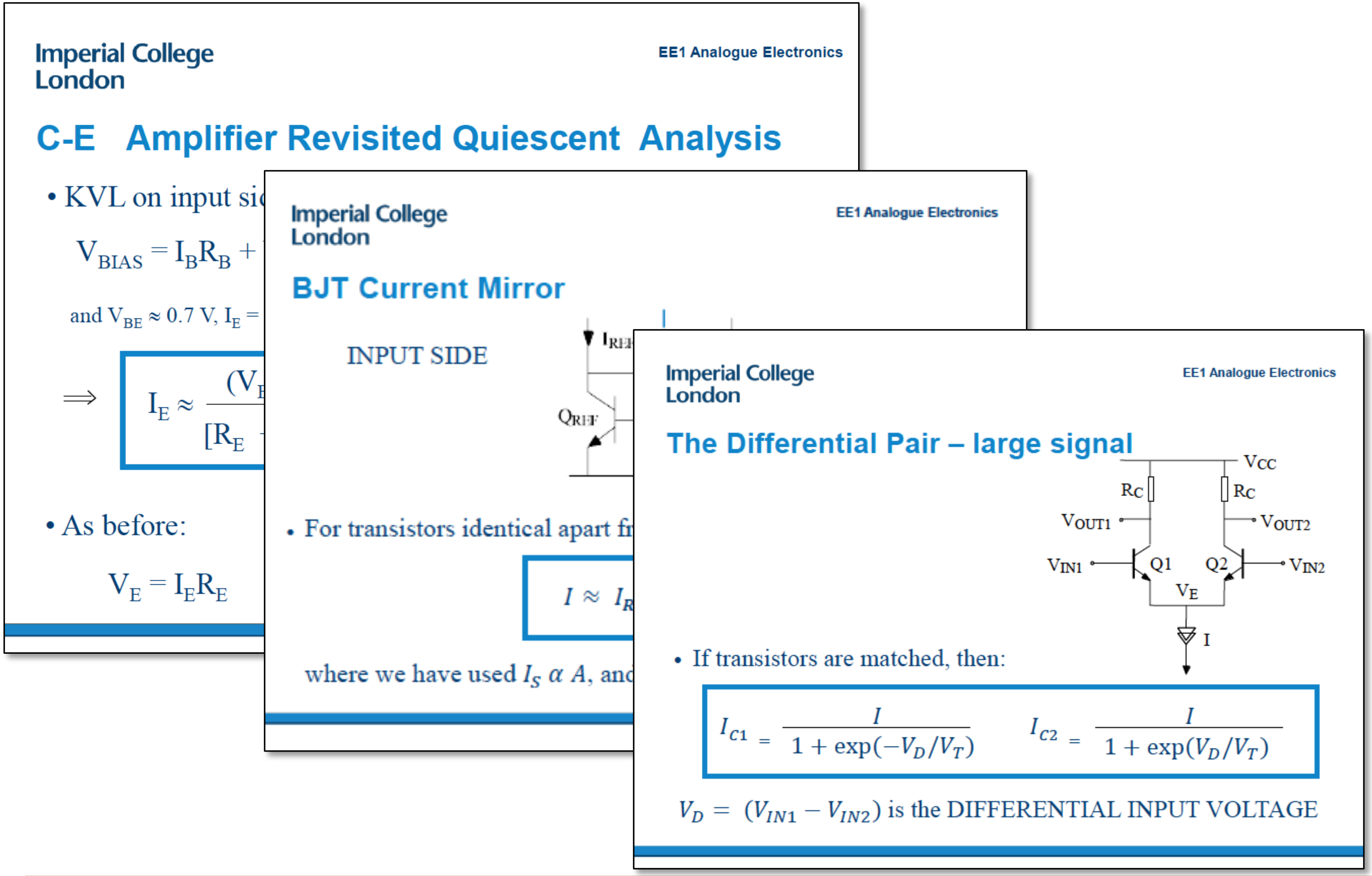
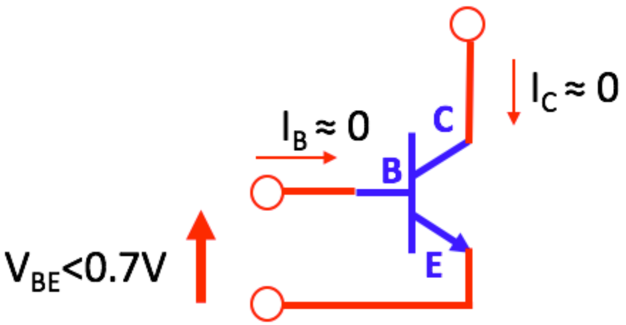
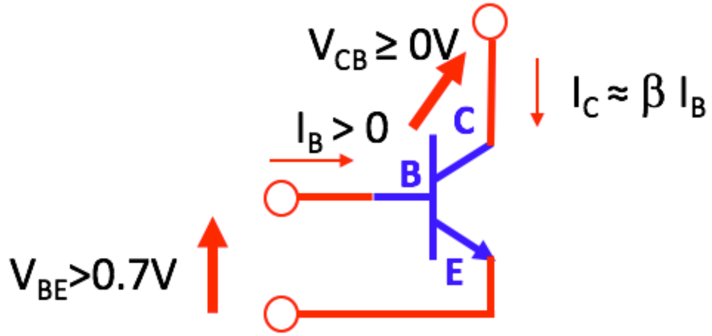
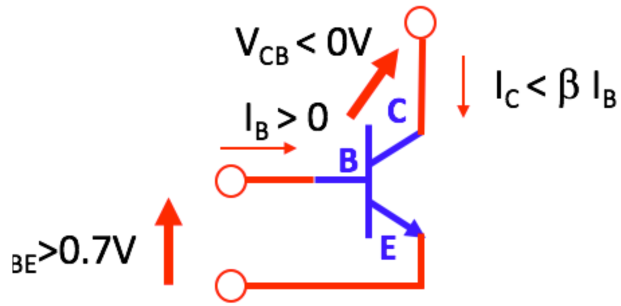
What you should know already?



Rules of thumb – Bipolar Junction Transistor (BJT)







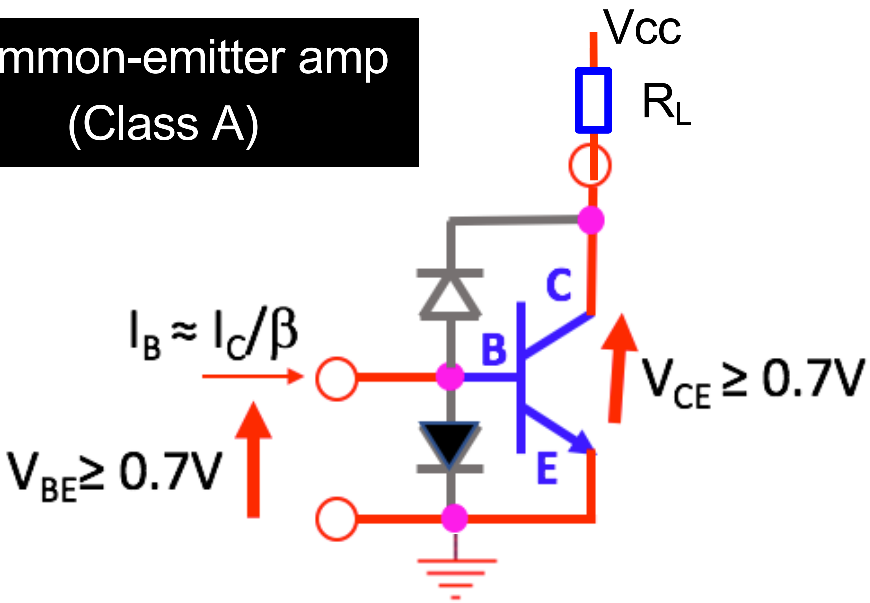
- $V_{BE} < 0.7V$
- Transistor OFF
- Near zero I_B and I_C (except leakage)
- Good for digital circuits

- $V_{BE} \geq 0.7V$
- BC junction diode reverse biased
- Transistor in linear/active region
- $I_C \approx \beta\ I_B$ applies
- Good for analogue circuits

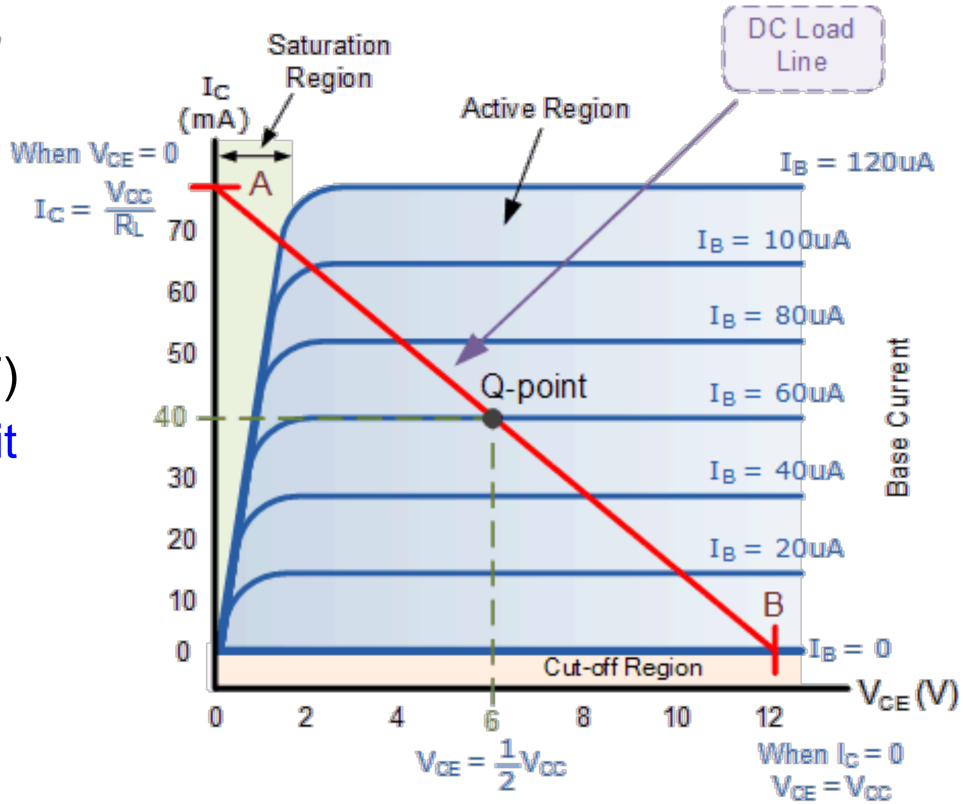
- $V_{BE} \geq 0.7V$
- BC junction diode NOT reverse biased
- Transistor in saturation region
- $I_C < \beta\ I_B$
- Good for digital circuits

NPN Transistor in Linear Region

Common-emitter amp
(Class A)

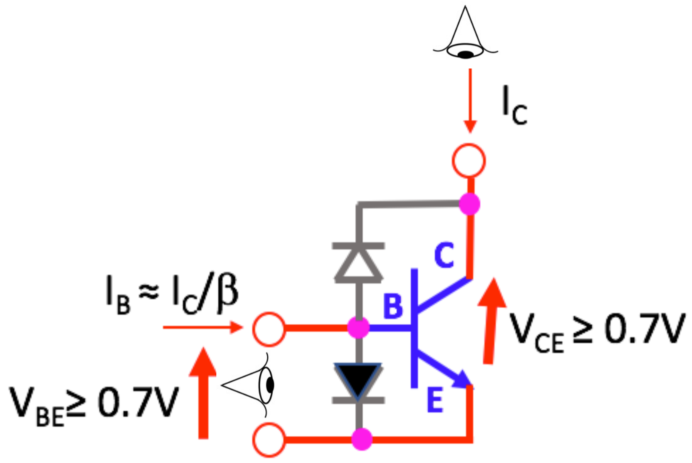


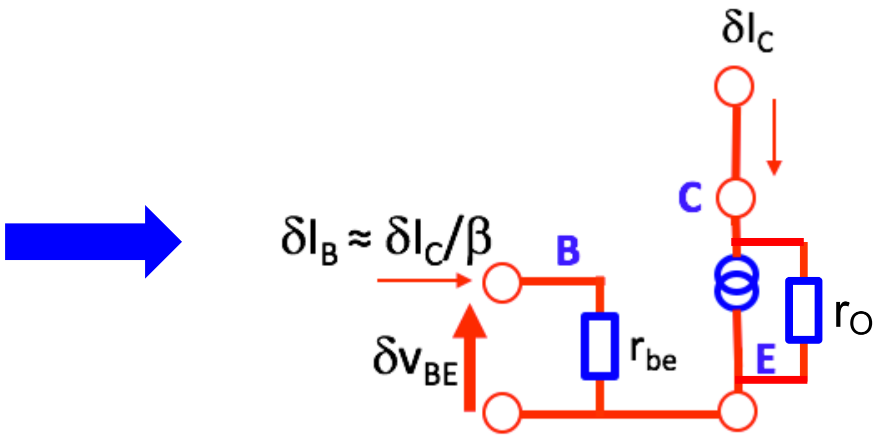
- Quiescent (DC) condition – **biasing**
- Ensures transistor in **linear region**
- Operating condition determined by I_C
- Use large signal model



- BE junction diode forward biased (ON)
- BC junction diode reverse biased (OFF)
- I_C is often determined by DC bias circuit
- I_B then fixed by β
- V_{CE} can take on any value between 0.3V and V_{CC}

Small signal behaviour of NPN transistor





- Quiescent I_C determine operating point
- Small signal model – 2 resistors r_{be} and r_O, and a current source

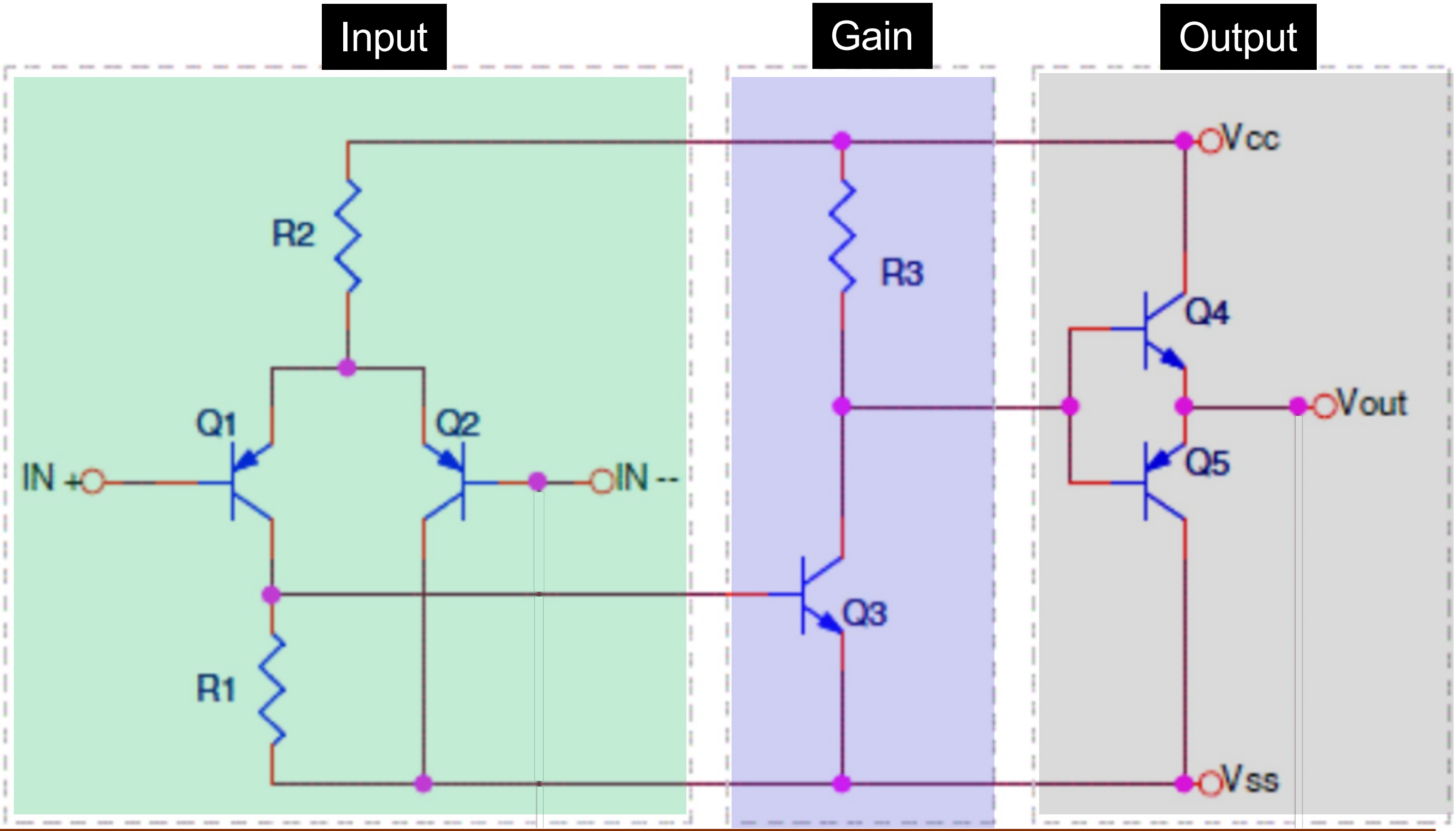
- $\delta i_B = \delta v_{BE} / r_{BE}$
- $\delta i_C = g_m \, \delta v_{BE}$
- $\delta i_E = \delta i_B + \delta i_C$

- r_o large - can be omitted

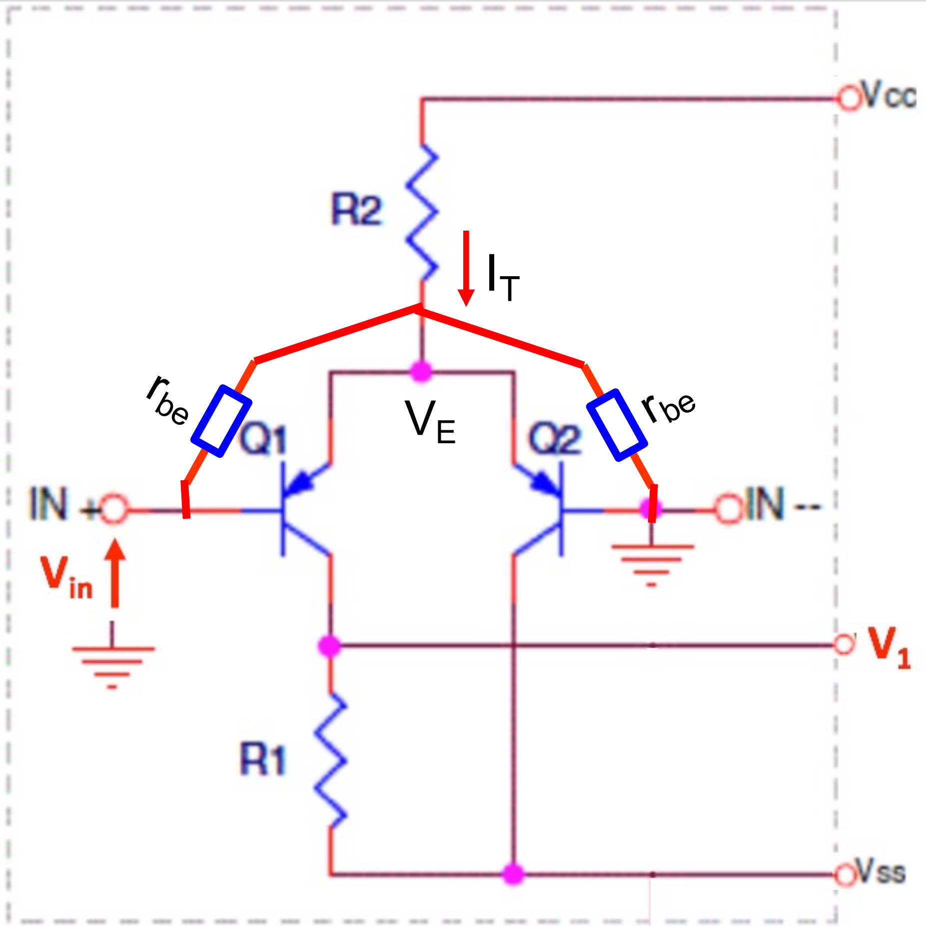
- current gain: $\beta = \delta i_C / \delta i_B$
- transconductance: $g_m = \delta i_C / \delta v_{BE} = I_C/V_T$
- Input resistance: $r_{be} = \delta v_{BE} / \delta i_B = \beta V_T/I_C$

Inside a typical op-amp

- Three stages architecture:
  1. **Differential input stage** – long-tail pair (Yr 1 Circuits part 2, adc_9, slides 8-14)
  2. **Voltage gain stage** – common emitter amp (adc_6, slides 3-7)
  3. **Output drive stage** – push-pull circuit



Differential Input Stage – differential gain



$A_{Vdiff} = \delta v_1 / \delta v_{in} = -½\, g_m * R_1$

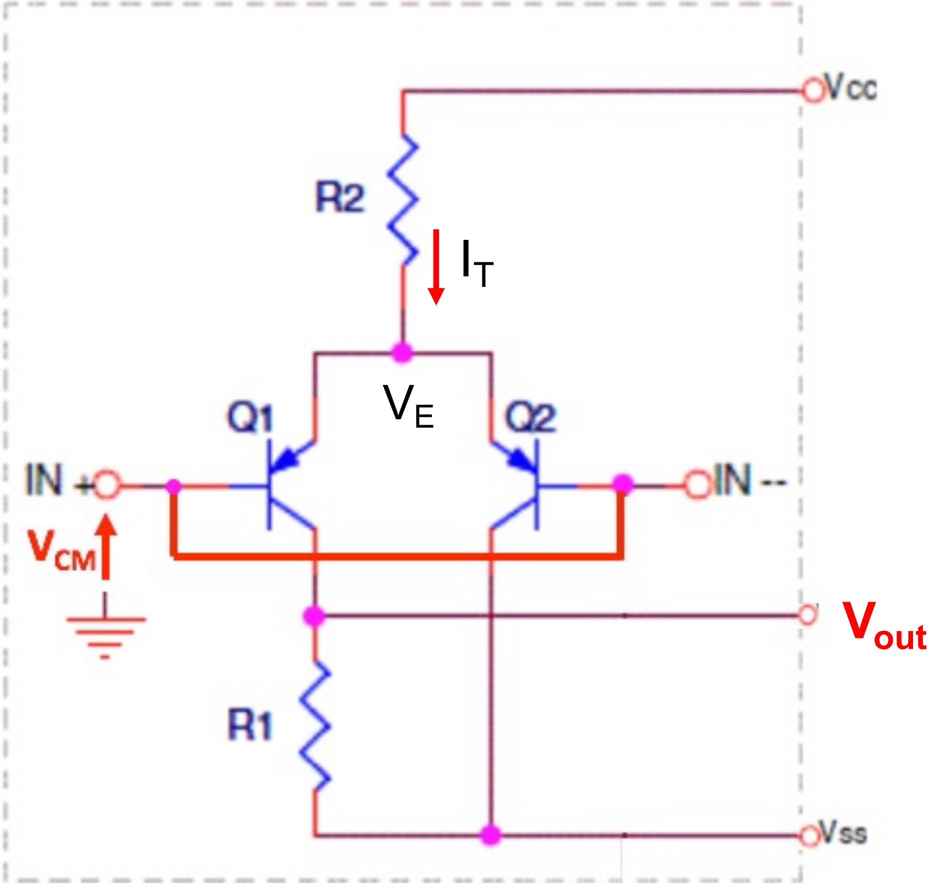
Consider $V_{in} = 0$, IN - is grounded

- $V_E \approx 0.7V$
- $I_T \approx (V_{CC} – 0.7) / R_2$
- $I_1 \approx I_2 \approx ½\, I_T \approx ½\, (V_{CC} – 0.7)/ R_2$
- $V_1 = R_1 * I_{C1} + V_{SS}$

Apply small input signal δV_{in}

- $\delta v_E \approx ½\, \delta v_{in}$
- $\delta\, i_T \approx ½\, \delta v_{in} / R_2 \approx 0$
- $\delta\, i_1 \approx - \delta\, i_2 = - g_m * ½\, \delta v_{in}$
- $\delta\, v_1 = R_1 * \delta\, i_1 = - R_1 * g_m * ½\, \delta v_{in}$

Differential Input Stage – common mode gain

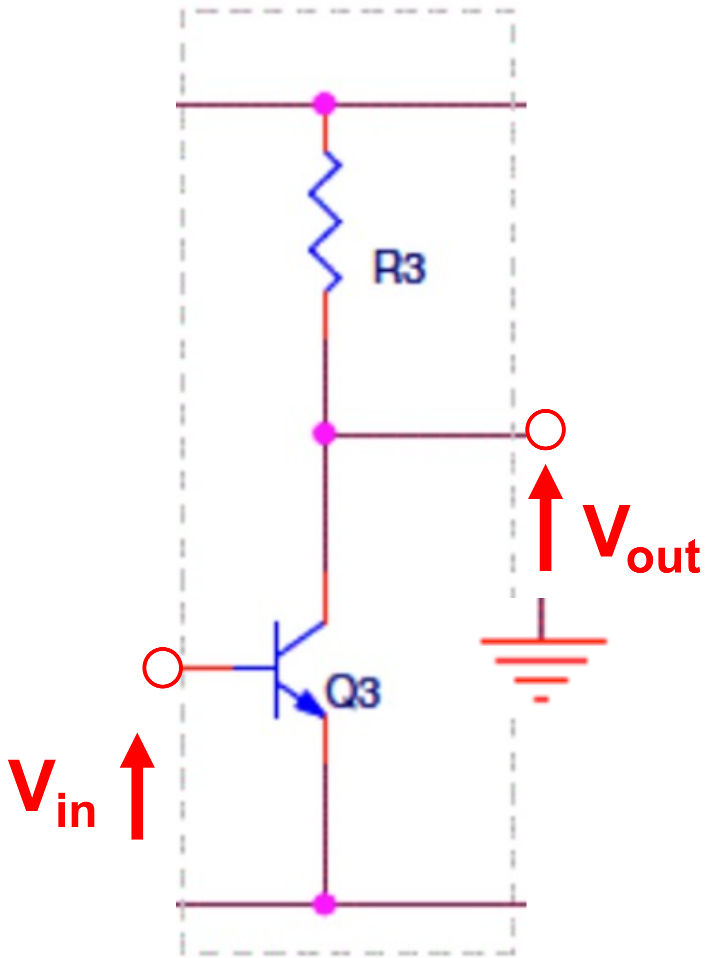


Apply v_{CM} to both inputs

- $\delta v_E \approx v_{CM}$
- $\delta i_T \approx - \delta v_E/R_2 = - v_{CM}/R_2$
- $\delta\, i_{C1} \approx \delta\, i_{C2} = ½\, \delta i_T = - ½\, v_{CM}/R_2$
- $\delta\, v_{out} \approx - R_1/2R_2 * v_{CM}$

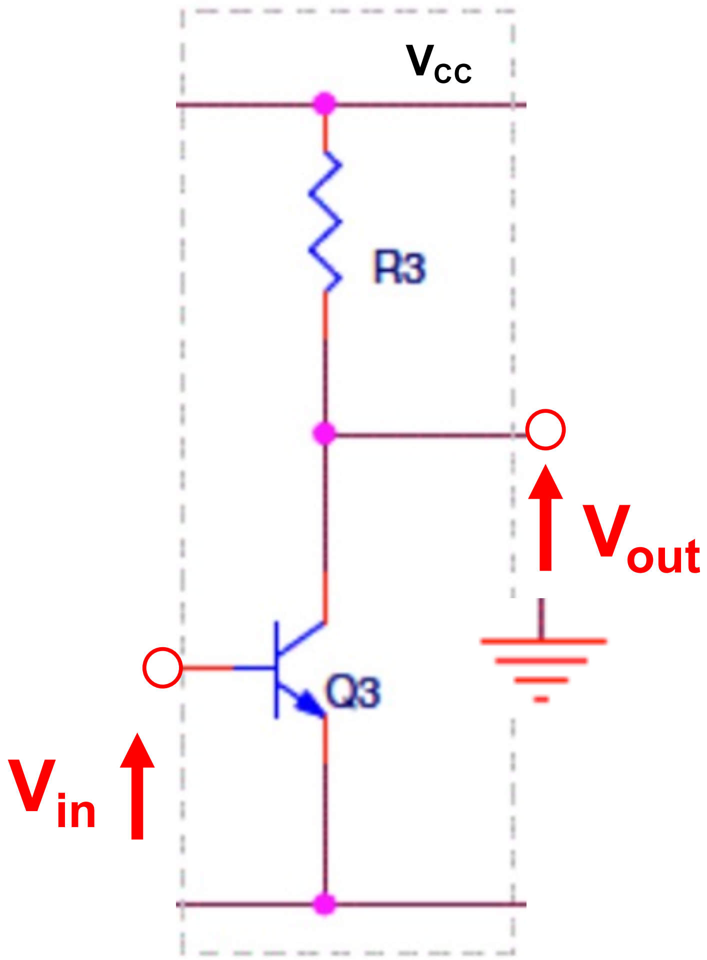
$$A_{Vcm} = \delta\, v_{out} / v_{CM} = - R_1/2R_2$$

Small Signal Gain stage



- Common Emitter amplifier (Yr 1st ADC part 2 Lecture 6, S7)
- $\delta v_{out} = - g_m \, \delta v_{in} * R_3$
- $A_V = \delta v_{out} / \delta v_{in} = - g_m R_3$
- Increase g_m and R_3
- Most of the voltage gain produced by this stage

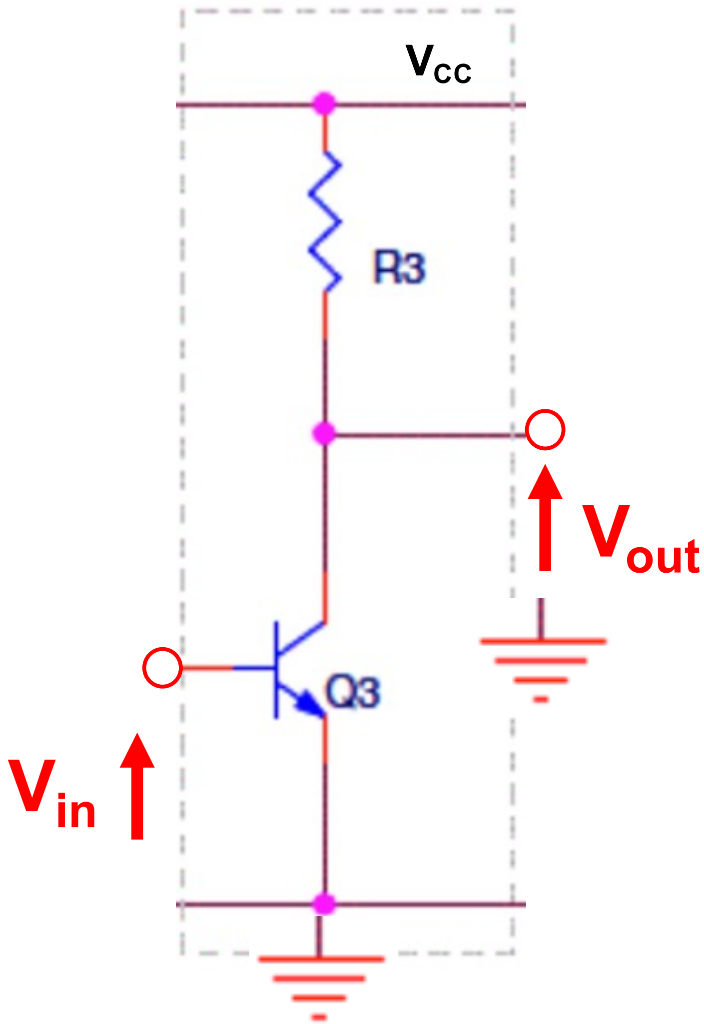
Gain stage is not suitable to drive output load



- Common-emitter amplifer is also called a **Class A amplifer** (name does not matter)
- R3 is the load (e.g. speaker)
- Transistor Q3 works throughout the entire cycle of a sine signal (360º)
- Very poor power efficiency:

$$efficiency\ \eta = \frac{power\ to\ load\ R_3}{Power\ from\ supply} < 25\%$$

Efficiency of a class A amplifier



- Assume Vout at quiescent (i.e. no input) is biased to be at Vcc/2
- Quiescent collector current I_{CQ} = (Vcc/2)*R3
- Average power drawn from supply voltage is:

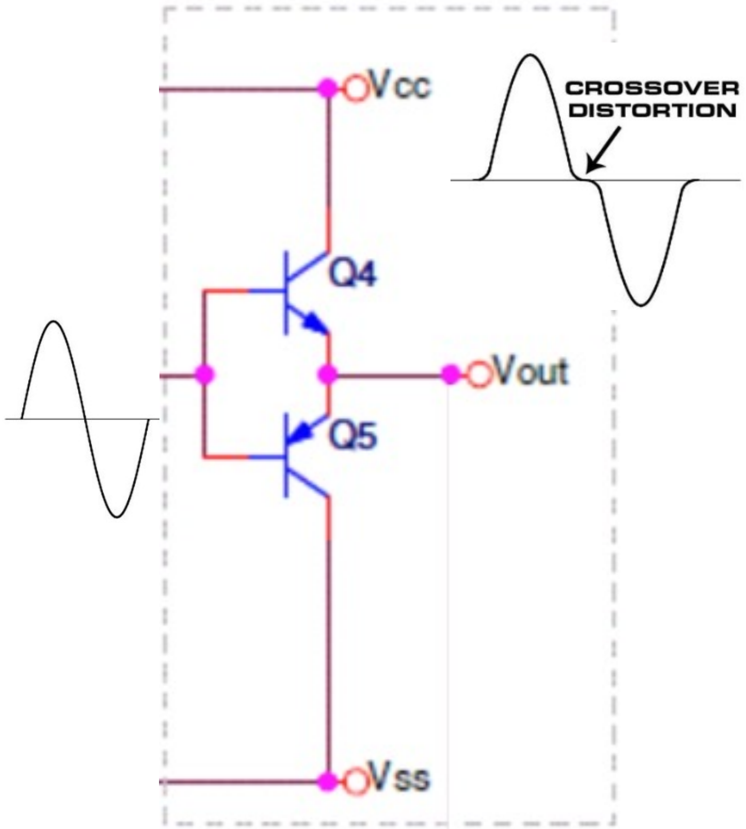
$$P_i(dc) = V_{CC}\ I_{CQ} = \frac{{V_{CC}}^2}{2 * R3}$$

- AC power delivered to load R3 is:

$$P_o(ac) = \frac{V_{out}(rms)^2}{R3}$$

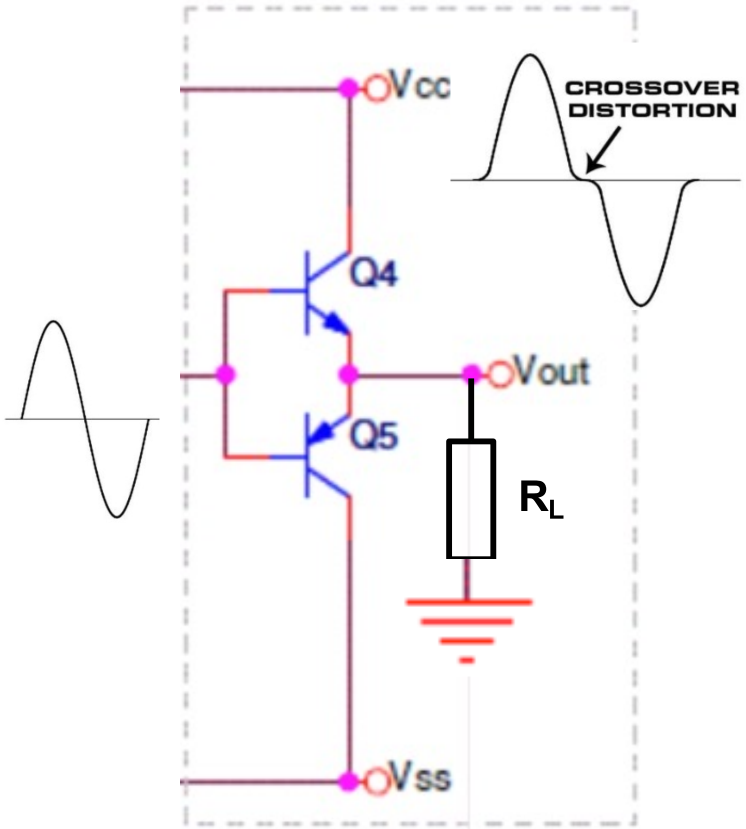
- P_o is maximum when $V_{out(pk-pk)}$ = V_{CC}, i.e. maximum output voltage swing
- Or $V_{out}(rms)$ = $V_{CC}/2\sqrt{2}$
- Therefore max $P_o(ac) = \frac{{V_{CC}}^2}{8R3}$
- Hence max $\eta = \frac{maximum\ \ P_o(ac)}{P_i(dc)} = \frac{{V_{CC}}^2/8R3}{{V_{CC}}^2/2R3} = \frac{1}{4}$

Output Stage



- Yr 1st ADC part 2 Lecture 6, S3-5
- Q4 is emitter follower (Common-Emitter) for sourcing current to Vout (PUSH)
- Q5 is another emitter follower for sinking current from Vout (PULL)
- This is known as a PUSH-PULL or class B amplifer circuit
- $\delta Vout \approx \delta V_{in,}$ i.e. its gain is 1
- Each transistor only operate for half cycle or 180º of a sinewave signal
- Further, Q4 and Q5 requires VBE > 0.7V to start conducting, therefore this amplifier has distortion.

Push-pull (Class B) amplifier efficiency



- Assume Vss = -Vcc for simplicity, output swing is $\pm V_{pk}$ and V_{pk} = Vcc.
- Q4 and Q5 conduct only for half cycle, hence

  DC supply power $P_i(dc) = \ V_{CC}\ I_{DC}$

- Average current is that of a full-wave rectified signal: $I_{DC} = \frac{2}{\pi} I_{pk}$ where I_{pk} is the peak output current.
- Hence $I_{DC} = \frac{2}{\pi}(\frac{V_{pk}}{R_L})$, and $P_i(dc) = \frac{2}{\pi}(\frac{V_{CC}{}^2}{R_L})$
- Output AC power is (from before)

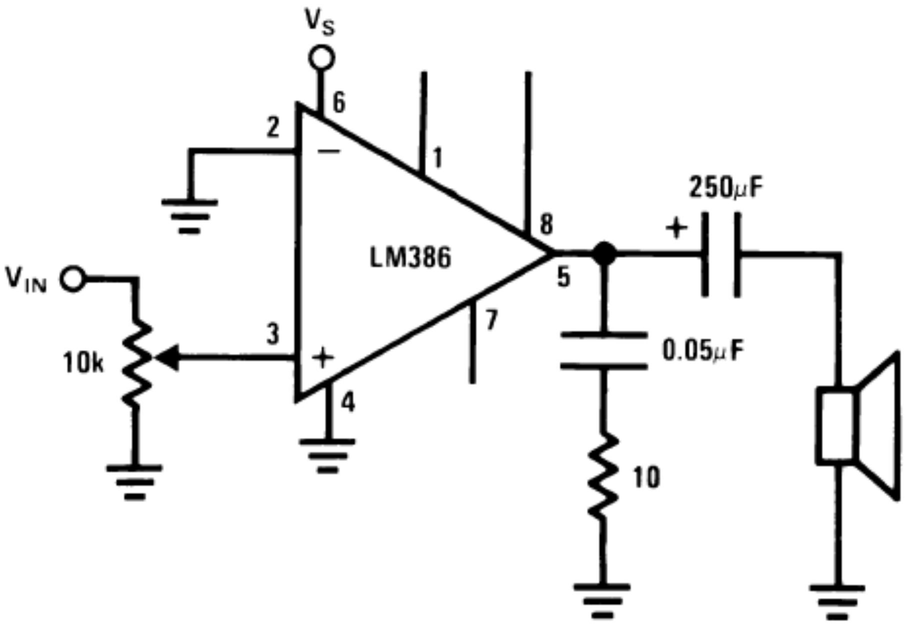
$$P_o(ac) = \frac{V_{out(pk-pk)}{}^2}{8R_L} = \frac{(2V_{pk})^2}{8R_L} = \frac{V_{CC}{}^2}{2R_L}$$

- Hence $\eta = \frac{P_o(ac)}{P_i(dc)} = \frac{V_{CC}{}^2/2R_L}{\frac{2}{\pi}(\frac{V_{CC}{}^2}{R_L})} = \frac{\pi}{4} = 78.5\%$

Driving 8Ω speaker with LM386

LM386
Low Voltage Audio Power Amplifier

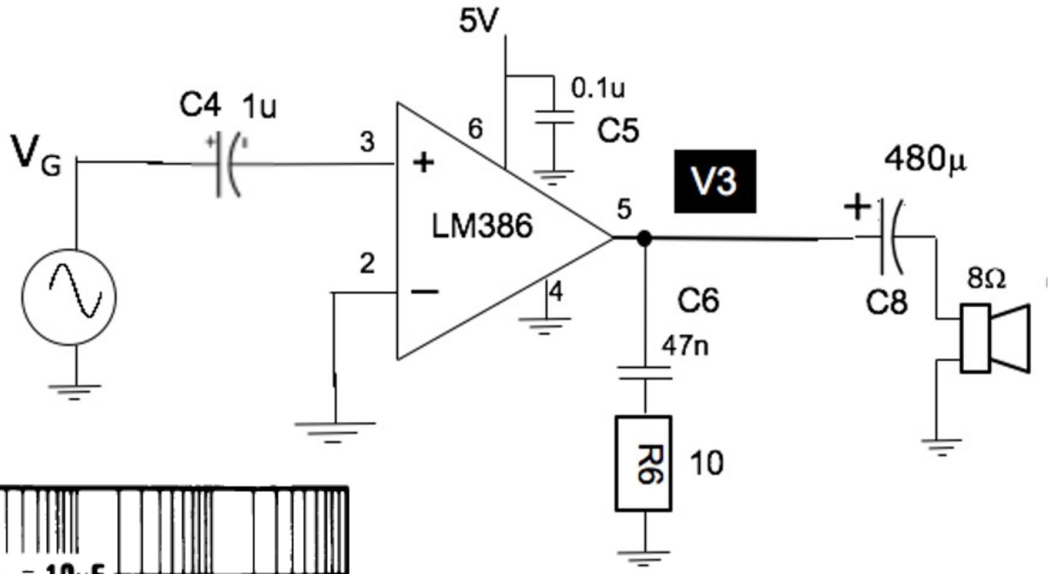
Amplifier with Gain = 20 Minimum Parts

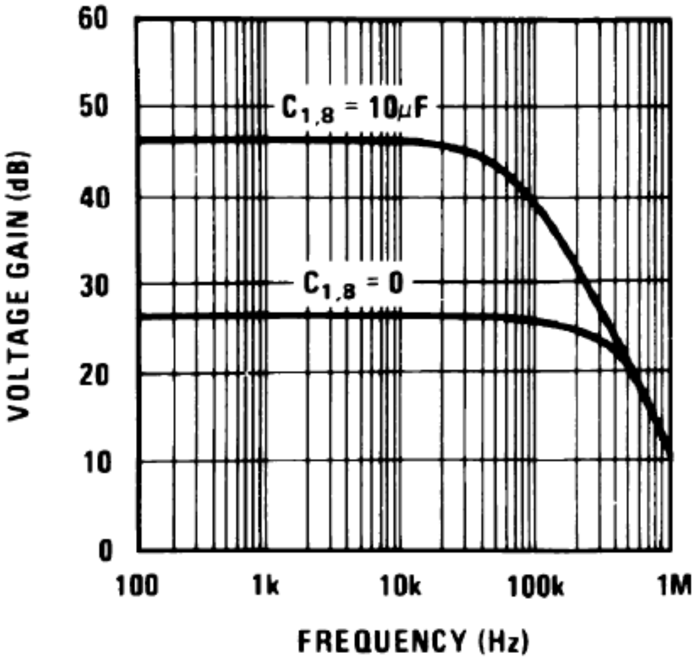


Features

- Battery operation
- Minimum external parts
- Wide supply voltage range: 4V–12V or 5V–18V
- Low quiescent current drain: 4mA
- Voltage gains from 20 to 200
- Ground referenced input
- Self-centering output quiescent voltage
- Low distortion: 0.2% (A_V = 20, V_S = 6V, R_L = 8Ω, P_O = 125mW, f = 1kHz)
- Available in 8 pin MSOP package

LM386 as a practical x20 amplifier (Lab 1)





- LM386 provides x20 gain
- Drives 8 ohm speaker
- C4 and C8 – blocking DC
- C6, R6, compensate for series inductance in 8 ohm speaker