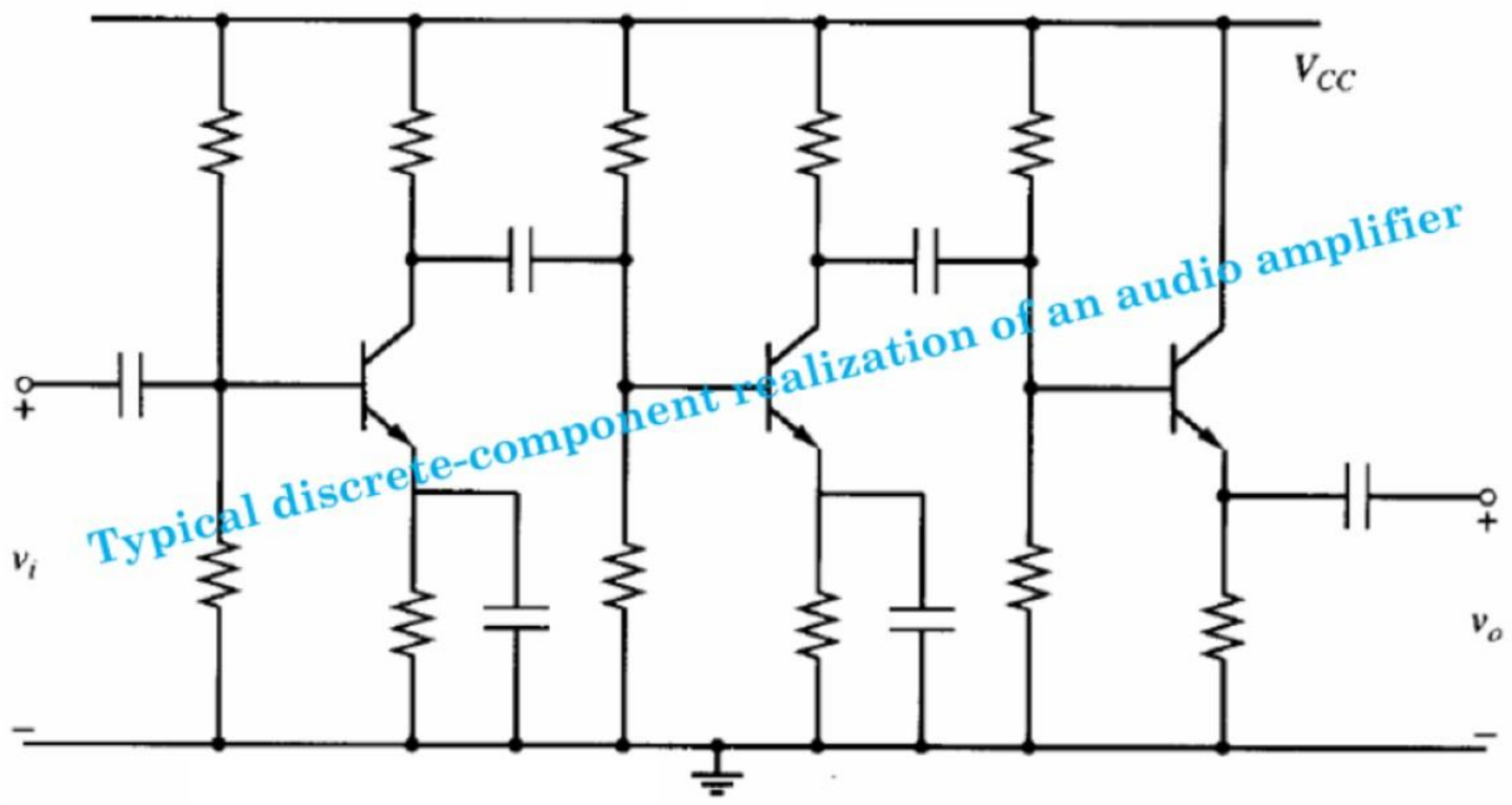
Multistage Amplifiers

Introduction


V_{CC}
Typical discrete-component realization of an audio amplifier
v_i
v_o
+
−
+
−

Summary and Comparisons of BJT Configurations

1. The **CE** configuration is the one best suited for **realizing the bulk of the gain** required in an amplifier. Depending on the magnitude of the gain required, either a single stage or a cascade of two or three stages can be used.
2. The low input resistance of the **CB amplifier** makes it useful only in **specific applications**. It has a much better high-frequency response than the CE amplifier. This superiority will make it **useful as a high-frequency amplifier**, especially when combined with the CE circuit.
3. The emitter follower (**CC**) finds application as a **voltage buffer for connecting a high resistance source to a low-resistance load and as the output stage in a multistage amplifier**, where its purpose is to equip the amplifier with a low output-resistance.

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Summary and Comparisons of MOSFET Configurations

- The **CS** configuration is the best suited for **realizing the bulk of the gain** required in an amplifier. Depending on the magnitude of the gain required, either a single stage or a cascade of two or three stages can be used.

- The low input resistance of the **CG** amplifier makes it useful only in **specific applications**. It has a much better high-frequency response than the CS amplifier. This superiority makes it **useful as a high-frequency amplifier**, especially when combined with the CS circuit.

- The **source follower** finds application as a voltage buffer **for connecting a high resistance source to a low-resistance load and as the output stage in a multistage amplifier** where its purpose is to equip the amplifier with a low output resistance.

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Multistage Amplifiers

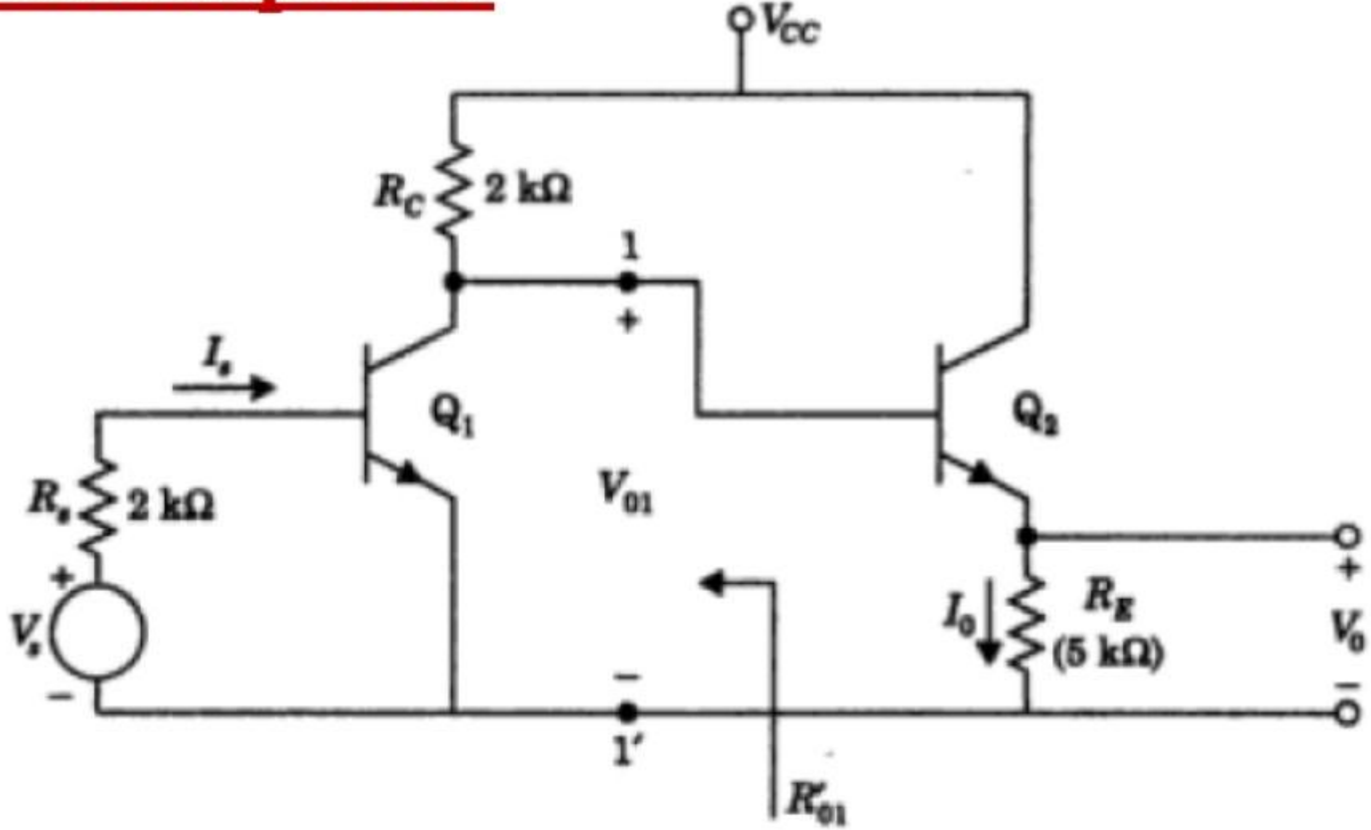
- In most practical electronic circuits/systems, the amplification provided by a single stage of amplifier is not sufficient, As was seen, the voltage gain of a single stage amplifier depends upon its resistance Rc which can not be increased beyond a limit due to constrains imposed by dc biasing.
- The input and output impedance of a single stage amplifier may not be suitable for the electronic circuit.
- These problem are taken care of by **connecting two or more amplifier stages in cascade to achieve larger voltage or current gain or suitable input and output impedance.**
- If it is desired to have a high voltage gain, then CE stages are cascaded.
- If high input impedance is required along with voltage gain, then first stage can be CC followed by CE stages (cascaded).

Multistage Amplifiers

1) **Cascaded Amplifier**
2) **Darlington pair (Special cascaded circuits)**
3) **Cascode Amplifier**

Multistage Amplifiers

1) Cascaded Amplifier



Two stage CE-CC Amplifier

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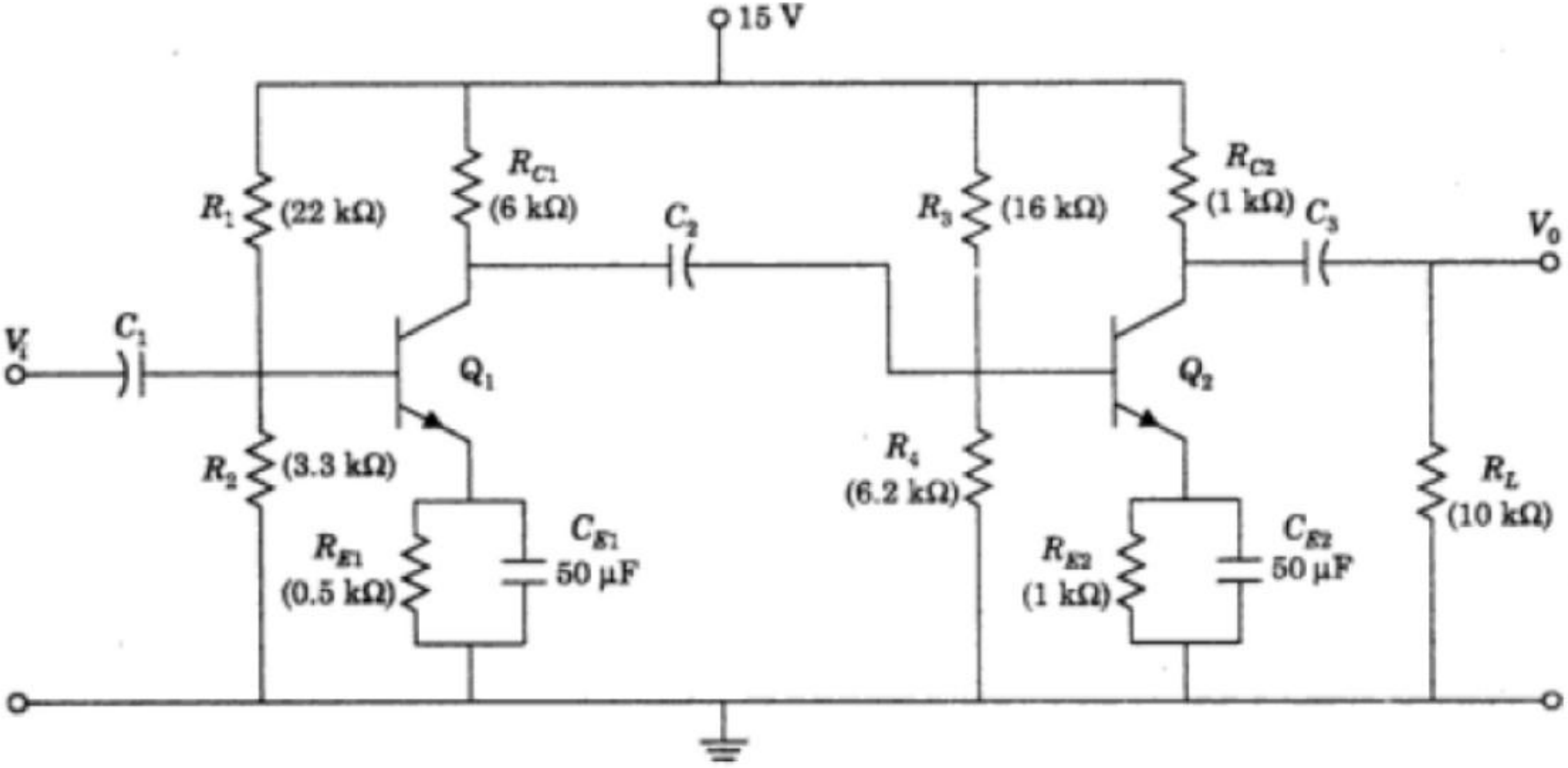
Multistage Amplifiers

1) Cascaded Amplifier



Two stage CE-CE Amplifier

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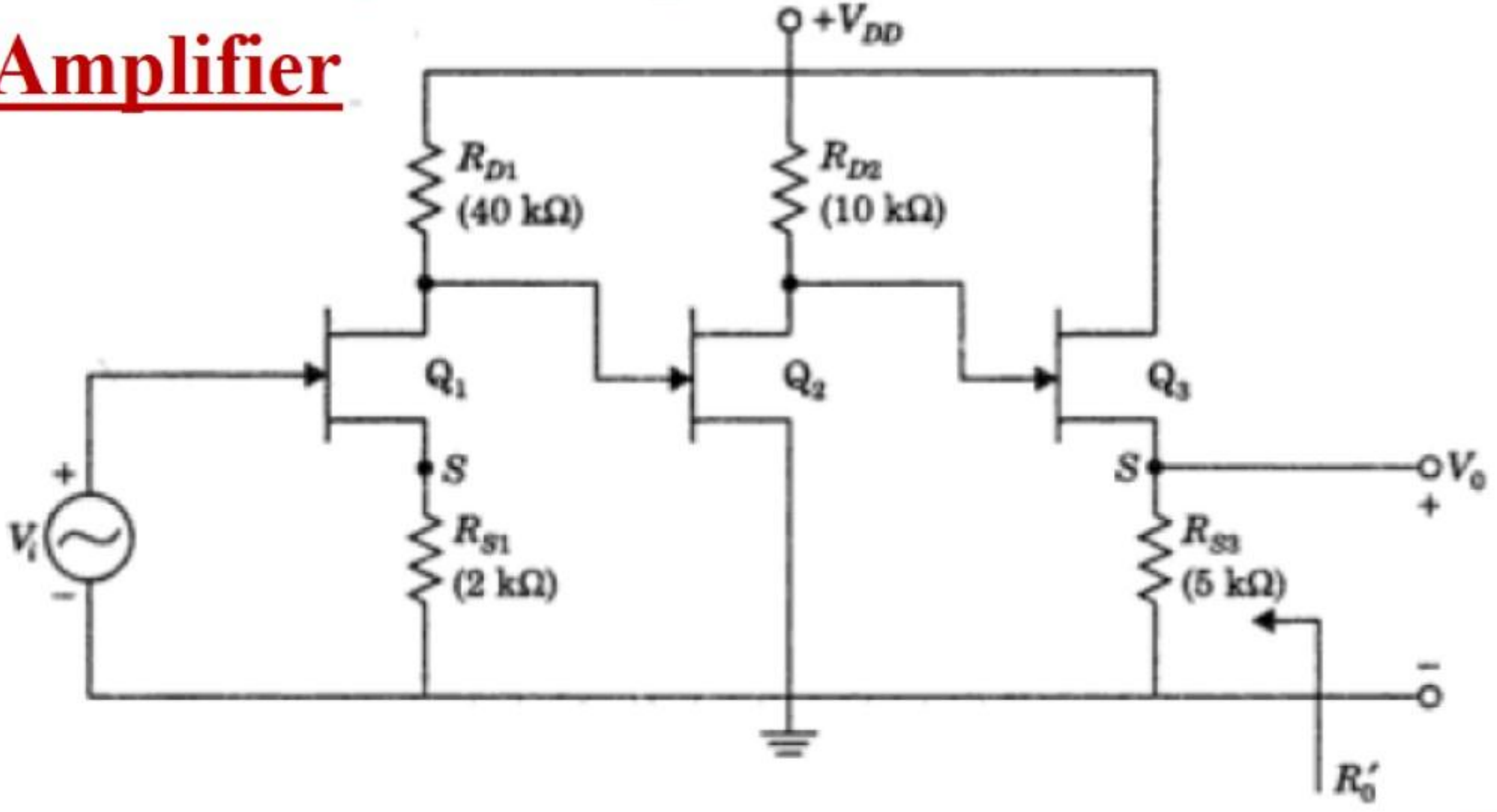
Multistage Amplifiers

1) Cascaded Amplifier



Three-stage Amplifier where first stage is CS with Rs, second stage is CS and third stage is CD amplifier.

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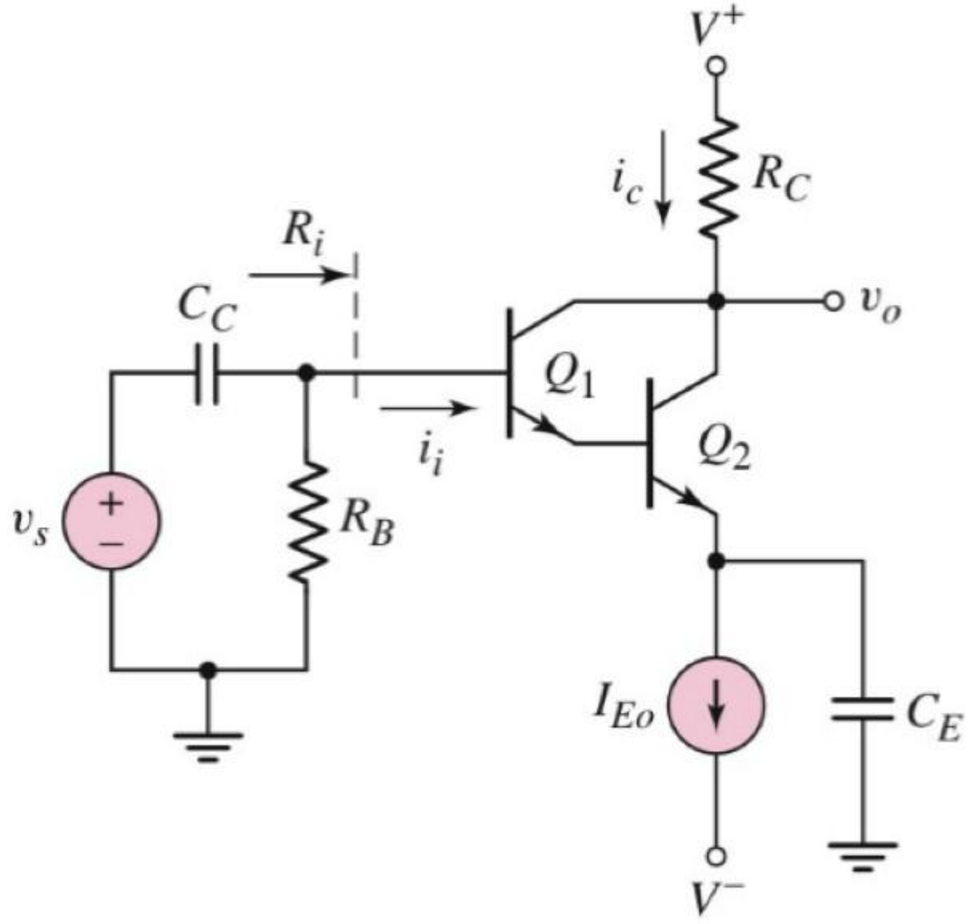
Multistage Amplifiers

2) Darlington pair

- Increased current; $I_C \cong \beta^2 I_B$
- High input resistance.



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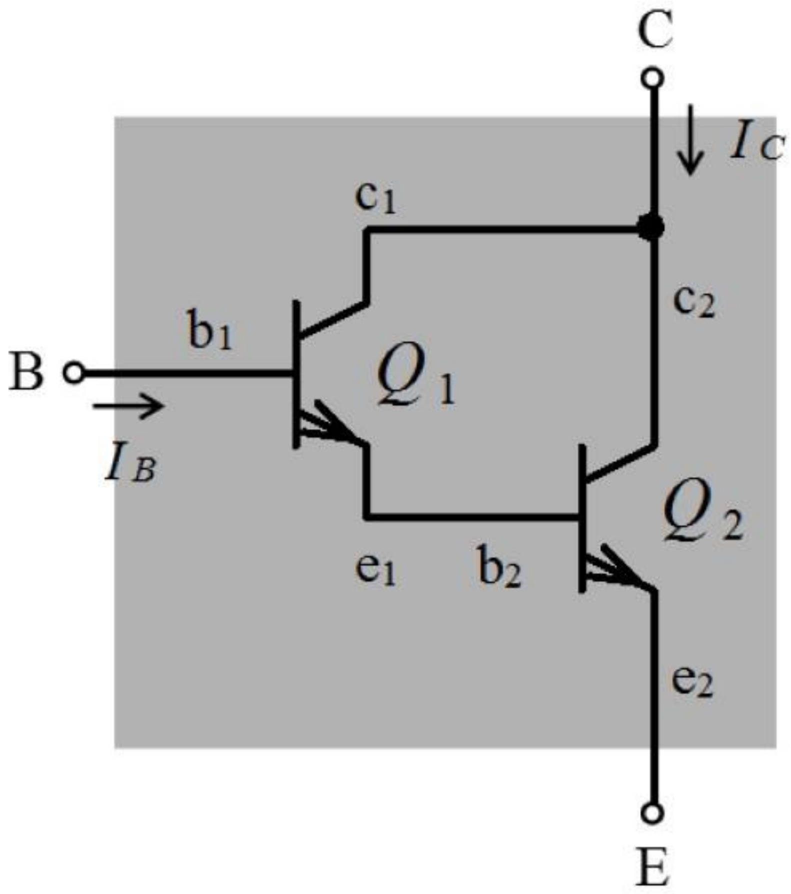
Darlington connection

- Provides high current gain : $I_C \cong \beta^2 I_B$
- High input resistance.



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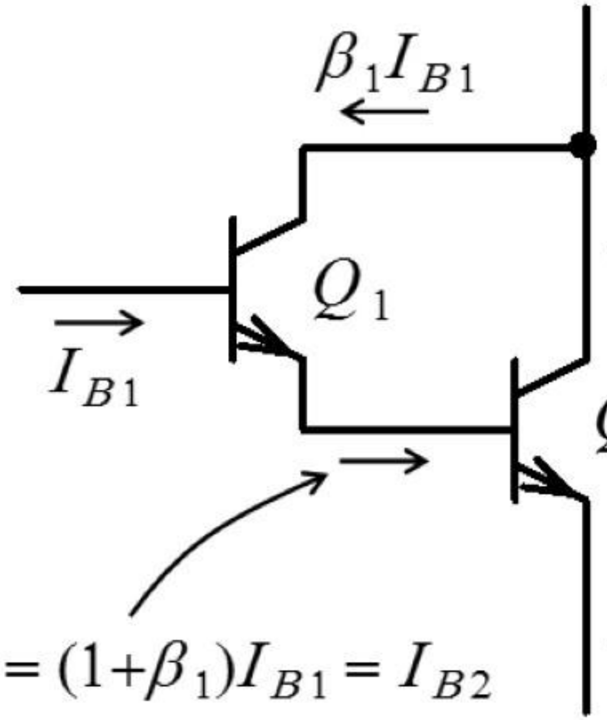
Currents in darlington pair



$$\downarrow I_{C1} + \mathrm{I}_{C2} = [\beta_1 + \beta_2(1+\beta_1)]I_{B1}$$

$$\downarrow I_{C2} = \beta_2 I_{B2} = \beta_2(1+\beta_1)I_{B1}$$

$$\downarrow I_{E2} = (1+\beta_2)I_{B2} = (1+\beta_1)(1+\beta_2)I_{B1}$$

$$I_{E1} = (1+\beta_1)I_{B1} = I_{B2}$$

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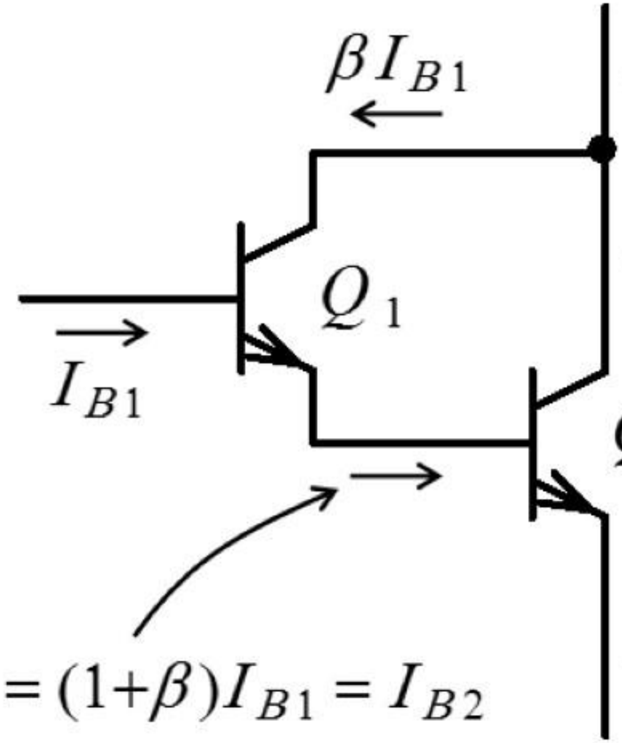
If $\beta_1 = \beta_2 = \beta$ and assuming β is large;



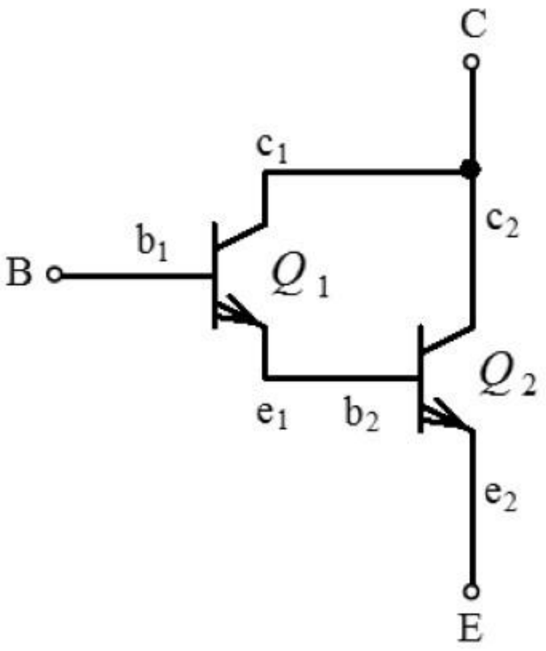
$$I_{C1} + I_{C2} \cong \beta^2 I_{B1}$$

$$I_{C2} = \beta I_{B2} = \beta(1+\beta) I_{B1}$$

$$I_{E2} = (1+\beta) I_{B2} = (1+\beta)^2 I_{B1}$$

$$I_{E1} = (1+\beta) I_{B1} = I_{B2}$$

Hybrid-π model (assuming $r_{o1} = r_{o2} = \infty$);



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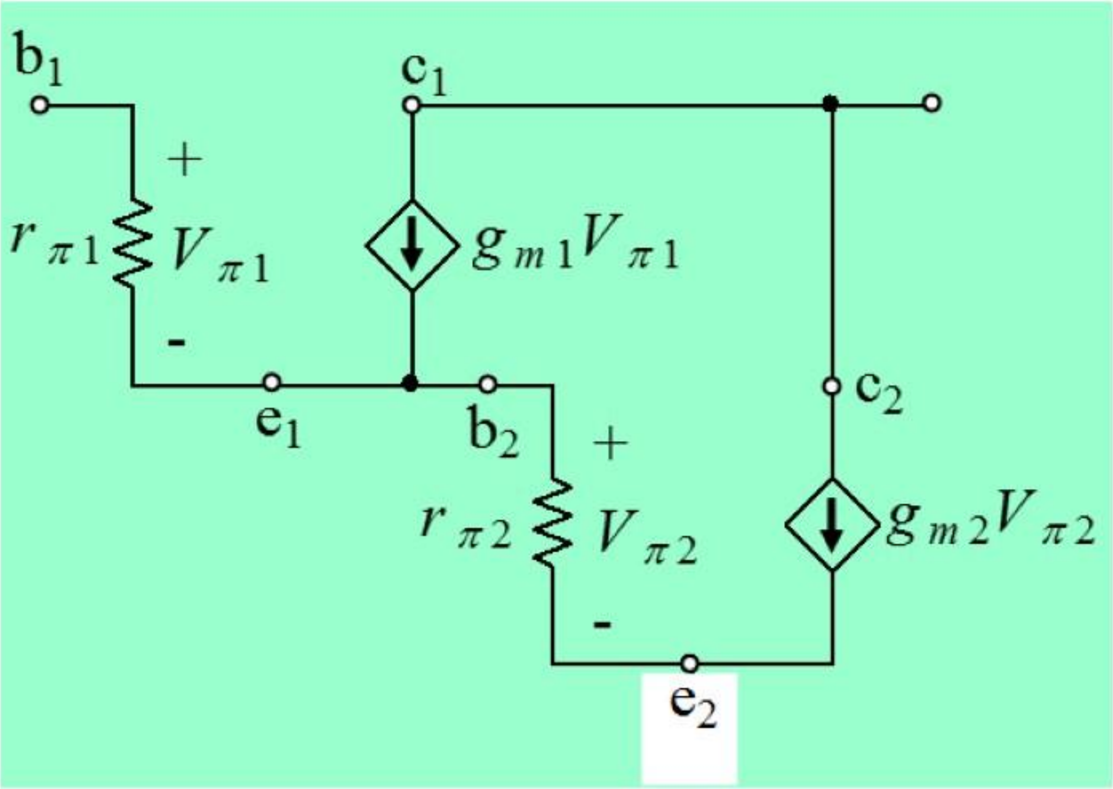

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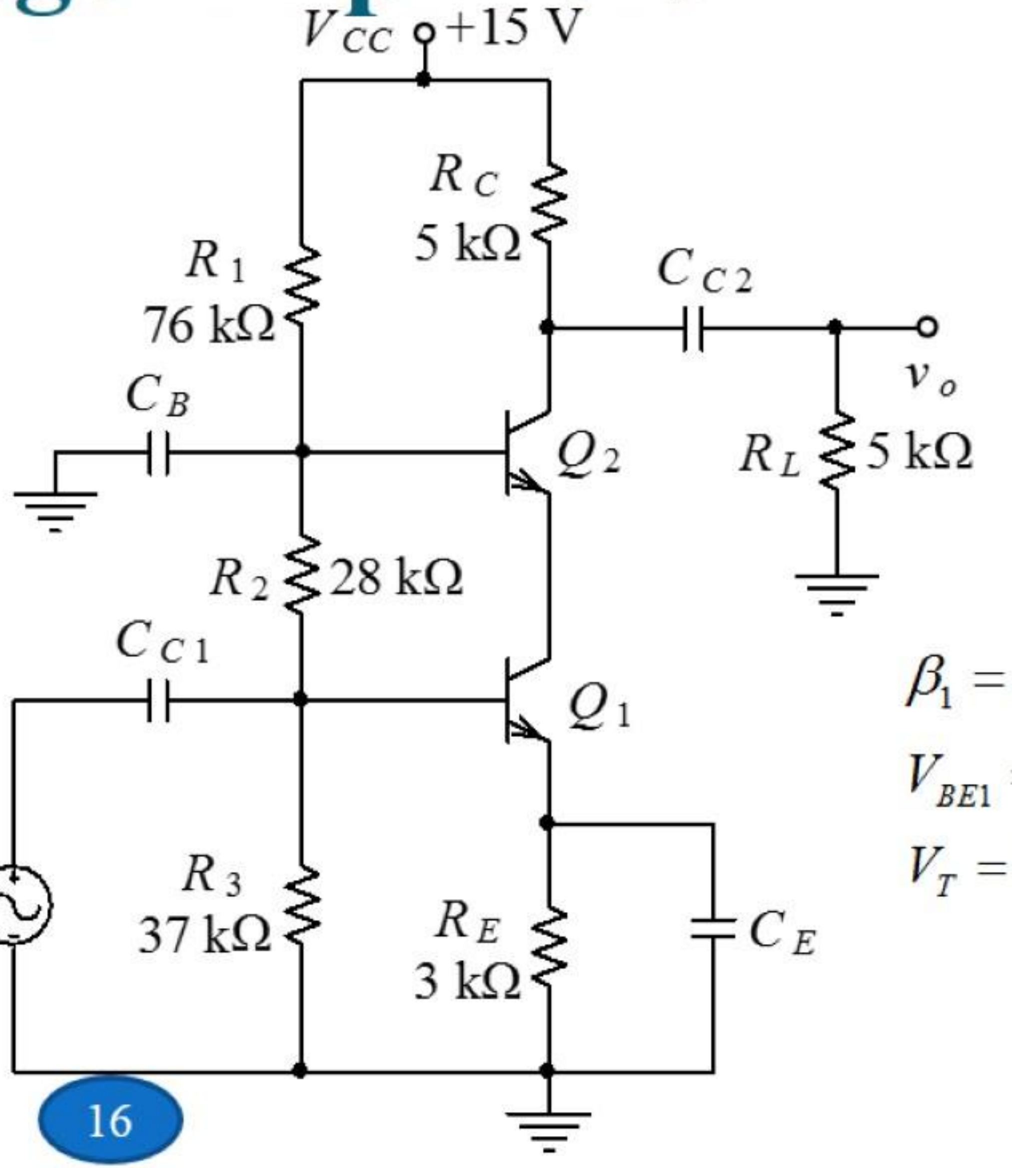
Multistage Amplifiers

3) Cascode Amplifier



$\beta_1 = \beta_2 = 150$

$V_{BE1} = V_{BE2} = 0.7\,\text{V}$

$V_T = 26\,\text{mV}$

A practical cascode amplifier.

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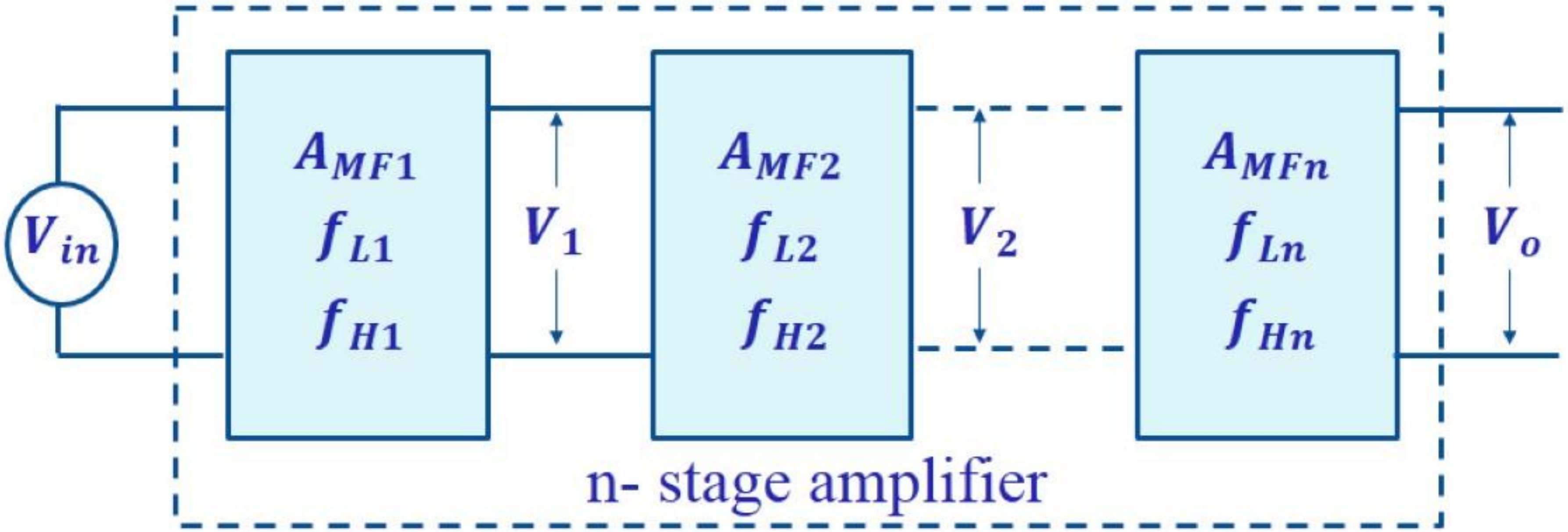
Cascaded Amplifier

To increases the Voltage Gain of the amplifier, multiple amplifiers are connected in cascade. But the Bandwidth will decrease.



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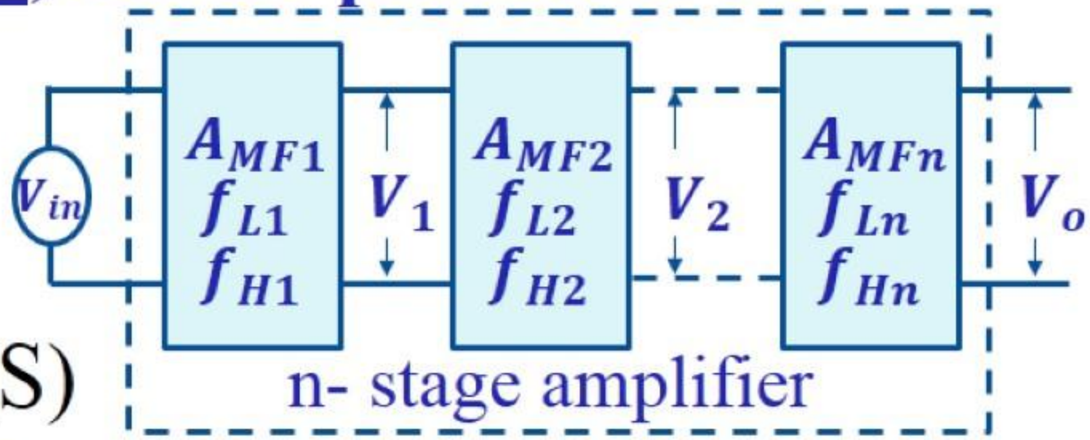
1. Overall Voltage Gain

(a) Assume that stages <u>do not interact</u>, it is the product of the gains of stages:

$$A_V(S) = \frac{V_o}{V_{in}} = \frac{V_1}{V_{in}}\frac{V_2}{V_1}\cdots\frac{V_o}{V_{n-1}}$$



$$A_V(S) = A_{V1}(S).\ A_{V2}(S).\ \ldots\ldots A_{Vn}(S)$$

(b) At low frequency, each amplifier is modeled by a single pole, then:

$$A_V(S) = \frac{A_{MF1}}{\left(1+\frac{\omega_{L1}}{S}\right)}\frac{A_{MF2}}{\left(1+\frac{\omega_{L2}}{S}\right)}\cdots\frac{A_{MFn}}{\left(1+\frac{\omega_{Ln}}{S}\right)}$$

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1. Overall Voltage Gain

(c) At high frequency, each amplifier is modeled by a single pole, then:

$$A_V(\mathrm{S}) = \frac{A_{MF1}}{\left(1+\frac{S}{\omega_{H1}}\right)} \frac{A_{MF2}}{\left(1+\frac{S}{\omega_{H2}}\right)} \cdots \frac{A_{MFn}}{\left(1+\frac{S}{\omega_{Hn}}\right)}$$

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2. Overall Mid-band Gain

Therefore, the Mid-band gain of the cascade amplifier is equal to the product of Mid-band gains of individual amplifiers as follows:

$$A_{MF}(\text{overall})=A_{MF1}.\,A_{MF2}.\;\;\ldots\ldots A_{MFn}$$

If identical stages,

$$A_{MF1} = A_{MF2} =.\;\;\ldots\ldots= A_{MFn} = A_{MF}$$

Therefore, the Mid-band gain of the cascade amplifier will be:

$$A_{MF}(\text{overall})= {A_{MF}}^{n}$$

Voltage Gain increases

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3. Overall Lower 3dB frequency

Lower 3dB frequency of the cascade amplifier is the frequency at which gain is reduced by -3 dB from its high frequency value.

$$\omega_L(\text{overall}) = \sqrt{\omega_{L1}^2 + \omega_{L2}^2 + \dots + \omega_{Ln}^2}$$

If identical stages,

$$\omega_{L1} = \omega_{L2} = \ldots\ldots = \omega_{Ln} = \omega_L$$

Therefore, Lower 3dB frequency of the cascade amplifier will be:

$$\omega_L(overall) = \omega_L / \sqrt{2^{\frac{1}{n}} - 1}$$

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4. Overall Higher 3dB frequency

Higher 3dB frequency of the cascade amplifier is the frequency at which gain is reduced by -3 dB from its low frequency value.

$$\omega_H(\text{overall}) = \frac{1}{\sqrt{\left(\frac{1}{\omega_{H1}}\right)^2 + \left(\frac{1}{\omega_{H2}}\right)^2 + \ldots + \left(\frac{1}{\omega_{Hn}}\right)^2}}$$

If identical stages,

$$\omega_{H1} = \omega_{H2} = . \;\ldots\ldots = \omega_{Hn} = \omega_H$$

Therefore, Higher 3dB frequency of the cascade amplifier will be:

$$\omega_H(overall) = \omega_H\sqrt{2^{\frac{1}{n}} - 1}$$

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5. Overall Bandwidth

$$B.W(overall) = \omega_H(overall) - \omega_L(overall)$$

If identical stages,

n	1	2	3	4	5
$\sqrt{2^{\frac{1}{n}} - 1}$	1	0.64	0.51	0.43	0.39

$$\boxed{\omega_L(overall) = \omega_L / \sqrt{2^{\frac{1}{n}} - 1}} > \omega_L$$

$$\boxed{\omega_H(overall) = \omega_H \sqrt{2^{\frac{1}{n}} - 1}} < \omega_H$$

Therefore, Bandwidth of the cascade amplifier will be:

$B.W(overall) < B.W(single)$ **Bandwidth decreases**

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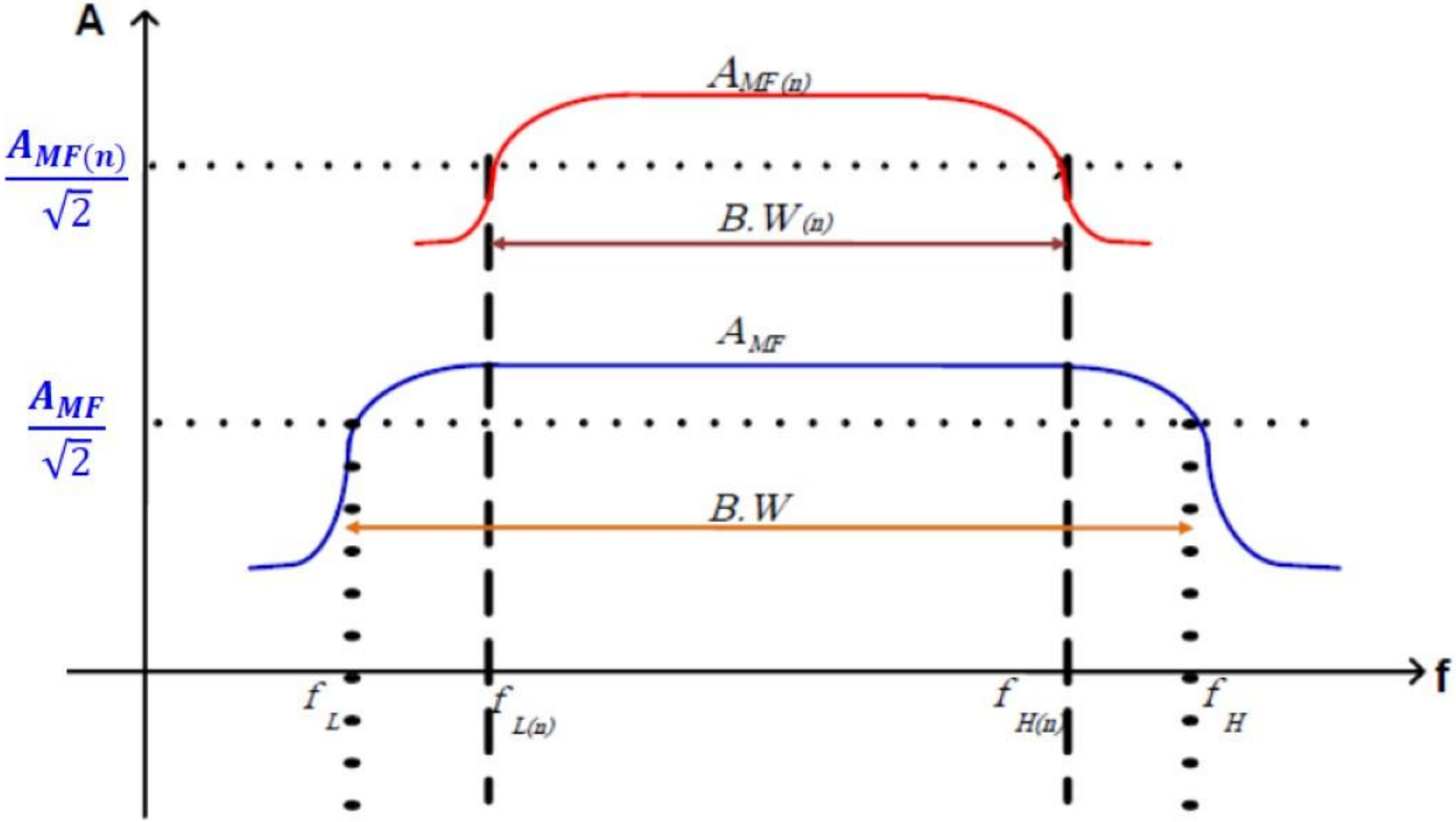
6. Frequency Response of Cascade Amplifier



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Example #1:

Calculate gain and bandwidth of a 2-stage amplifier with

$$A_{V1}=\frac{500}{\left(1+\frac{S}{2000}\right)} \qquad A_{V2}=\frac{250}{\left(1+\frac{S}{4000}\right)}$$

Solution:

$$A_V(\mathrm{S}) = \frac{125000}{\left(1+\frac{S}{2000}\right)\left(1+\frac{S}{4000}\right)}$$

$$A_{MF}(\text{overall})=(500)(250) = 125000 = 102\ dB$$

$$\omega_H(\text{overall})= \frac{1}{\sqrt{\left(\frac{1}{2000}\right)^2+\left(\frac{1}{4000}\right)^2}} = 1789\ rad/s$$

$$f_H(\text{overall})= 285\ Hz$$

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Example #2:

Three identical stages have an overall upper 3dB frequency of 20 KHZ and a lower 3dB frequency of 20 HZ. What are f_L and f_H of each stage? Assume non-interacting stages.

Solution:

$$n = 3, f_L(overall) = 20 \text{ Hz}, f_H(overall) = 20 \text{ KHz}$$

$$f_L(overall) = f_L/\sqrt{2^{\frac{1}{3}} - 1} = f_L/0.51$$

$$f_L = f_L(overall) * 0.51 = 20*0.51 = 10.2 \text{ Hz}$$

$$also, f_H = f_H(overall)/\sqrt{2^{\frac{1}{3}} - 1} = 20K/0.51 = 39.2 \text{ KHz}$$

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<u>Interacting Stages:</u> **If in a cascade of stages the input impedance of one stage is low enough to act as an appreciable shunt on the output impedance of the preceding stage, then it is no longer possible to isolate stages. (Millman Halkias - Integrated Electronics, Sec 12.6)**

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Coupling Methods in Multistage Amplifiers

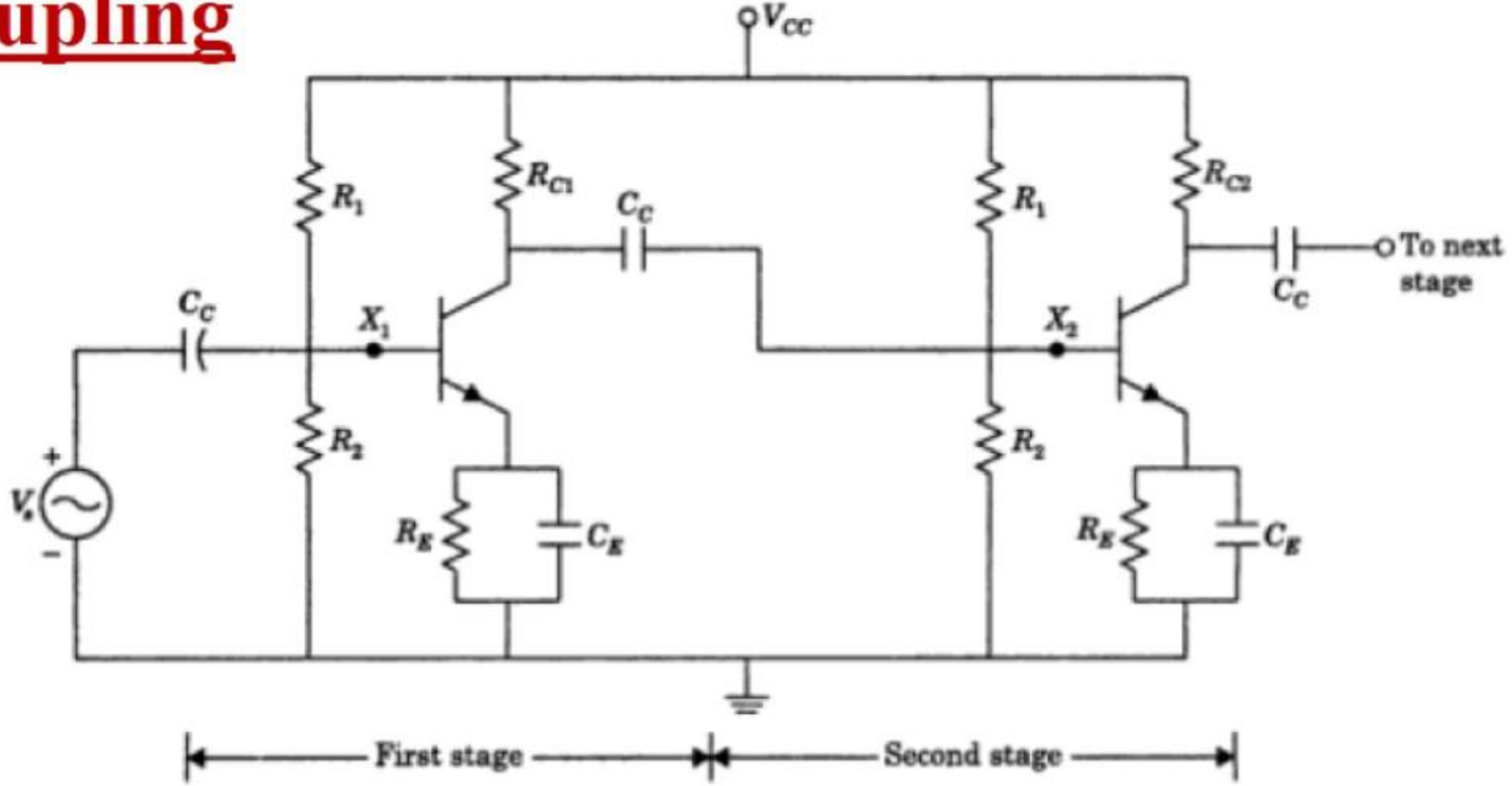
- The output of first stage in a multistage Cascaded amplifier is connected to the input of the next stage through a coupling device.
- The three basic types of couplings used are;
  1) **Capacitive Coupling**
  2) **Direct coupling**
  3) **Transformer coupling**

Coupling Methods in Multistage Amplifiers

- A good coupling network should block the dc signals so that the dc bias condition of the next stage is not disturbed.
- It should permit only the ac signals to be passed to the next stage without any distortion or loss of signal.
- If the coupling device is such that its impedance varies with frequency (for capacitor and inductor) then the frequency response characteristics of the amplifier are affected.

Coupling Methods in Multistage Amplifiers

1) Capacitive coupling



A two-stage Capacitive Coupling amplifier.

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Coupling Methods in Multistage Amplifiers

1) Capacitive coupling

- Capacitive coupling prevents the dc bias of one stage from affecting that of the other but allows the ac signal to pass without attenuation because $X_C = 0\ \Omega$ at the frequency of operation.

- Capacitive coupling is the most commonly used coupling method and provides excellent frequency response at the audio range of frequencies.

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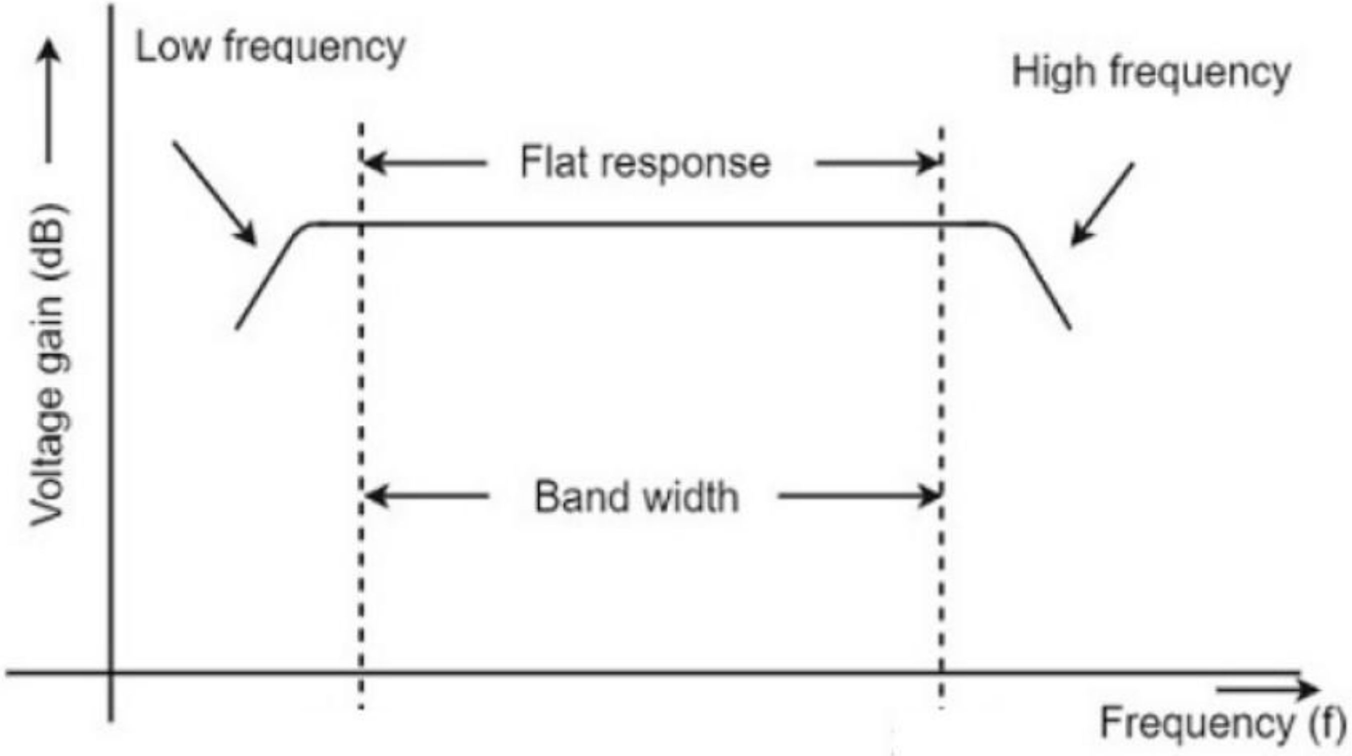
Coupling Methods in Multistage Amplifiers

1) Capacitive coupling



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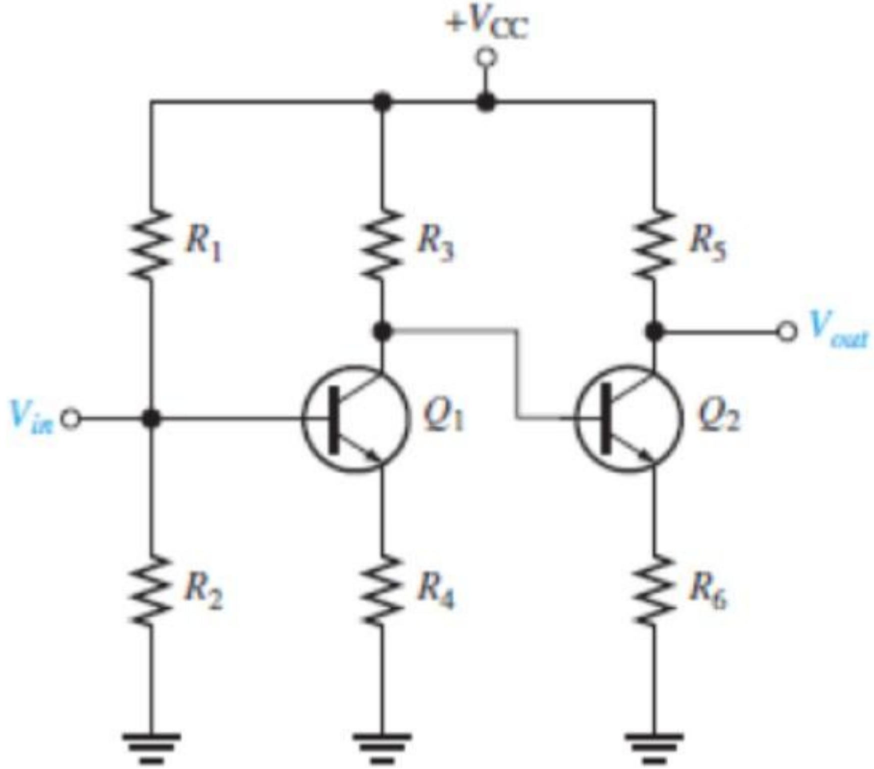
Coupling Methods in Multistage Amplifiers

2) Direct coupling

- **The output of the first stage is directly connected as input to the next stage without any coupling device.**
- **Very low frequency signals(<10 Hz) and even dc signals can be amplified.**
- **These amplifier are very useful for low frequency applications.**



A basic two-stage direct-coupled amplifier.

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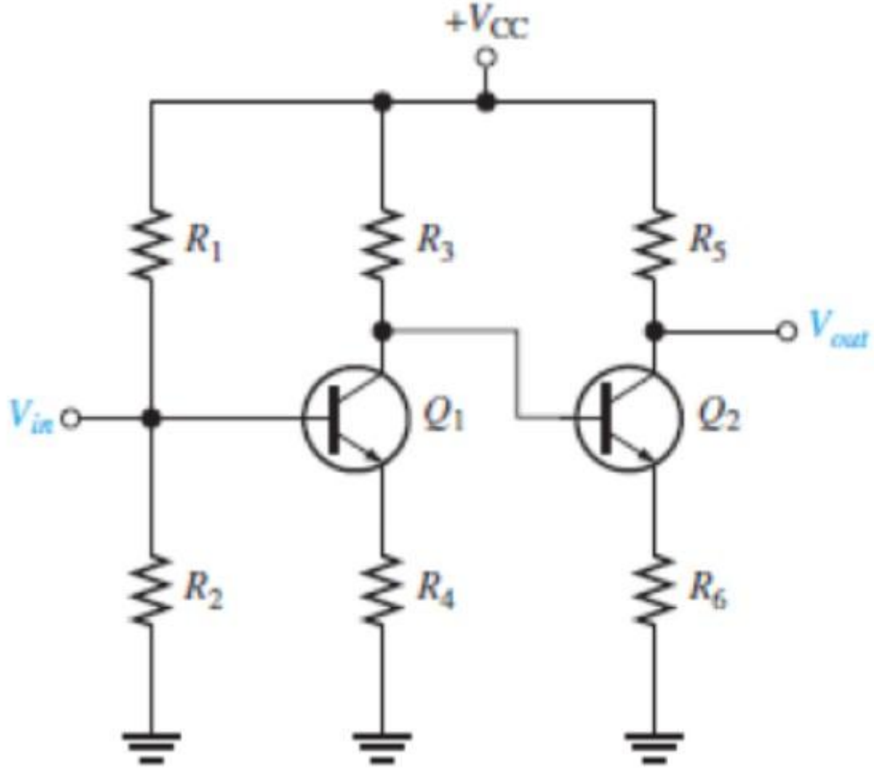
Coupling Methods in Multistage Amplifiers

2) Direct coupling

- **As an example, consider the use of a thermocouples will be very low (in µV) and, therefore, needs to be amplified. It will also be slowly varying as the temperature of the furnace varies slowly.**
  - **The direct coupling, however is very useful in differential amplifiers which form the basic block of an operational amplifiers.**



A basic two-stage direct-coupled amplifier.

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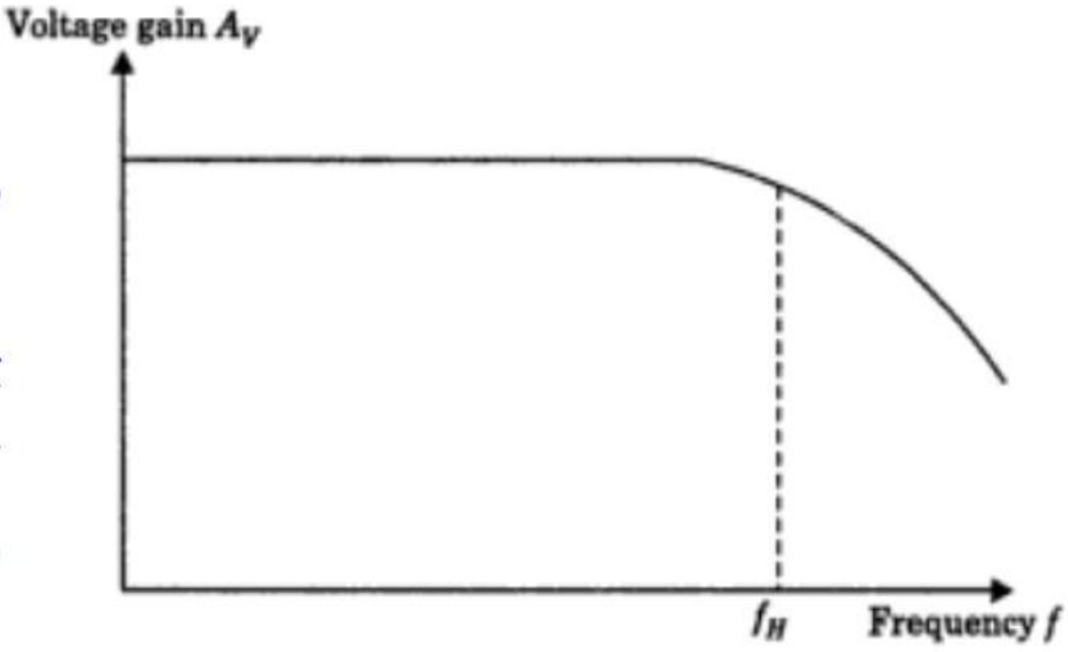
Coupling Methods in Multistage Amplifiers

2) Direct coupling

- The frequency response of a direct-coupled amplifier is shown in figure.
- The frequency response of the direct coupled amplifier is similar to low pass filter and hence it is also Known as “Low Pass Amplifier”.
- The amplification of DC (zero frequency) is possible only by this amplifier.



Frequency response of a direct-coupled amplifier

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Coupling Methods in Multistage Amplifiers

2) Direct coupling

- **Advantages**

Direct-coupled amplifiers can be used to amplify low frequencies all the way down to dc (0 Hz) without loss of voltage gain because there are no capacitive reactance in the circuit.

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Coupling Methods in Multistage Amplifiers

2) Direct coupling

- **Disadvantages**

- One major drawback of this type of coupling is that as dc signals are not blocked, the dc current from one stage also goes to the next stage thereby disturbing the quiescent conditions of the next stage.
- Further any variations in the dc voltages and currents due to temperature variations or change of device are passed on to the next stage.
- The temperature stability of such amplifiers is poor, although it can be improved to a certain extent by using negative feedback in the circuit.

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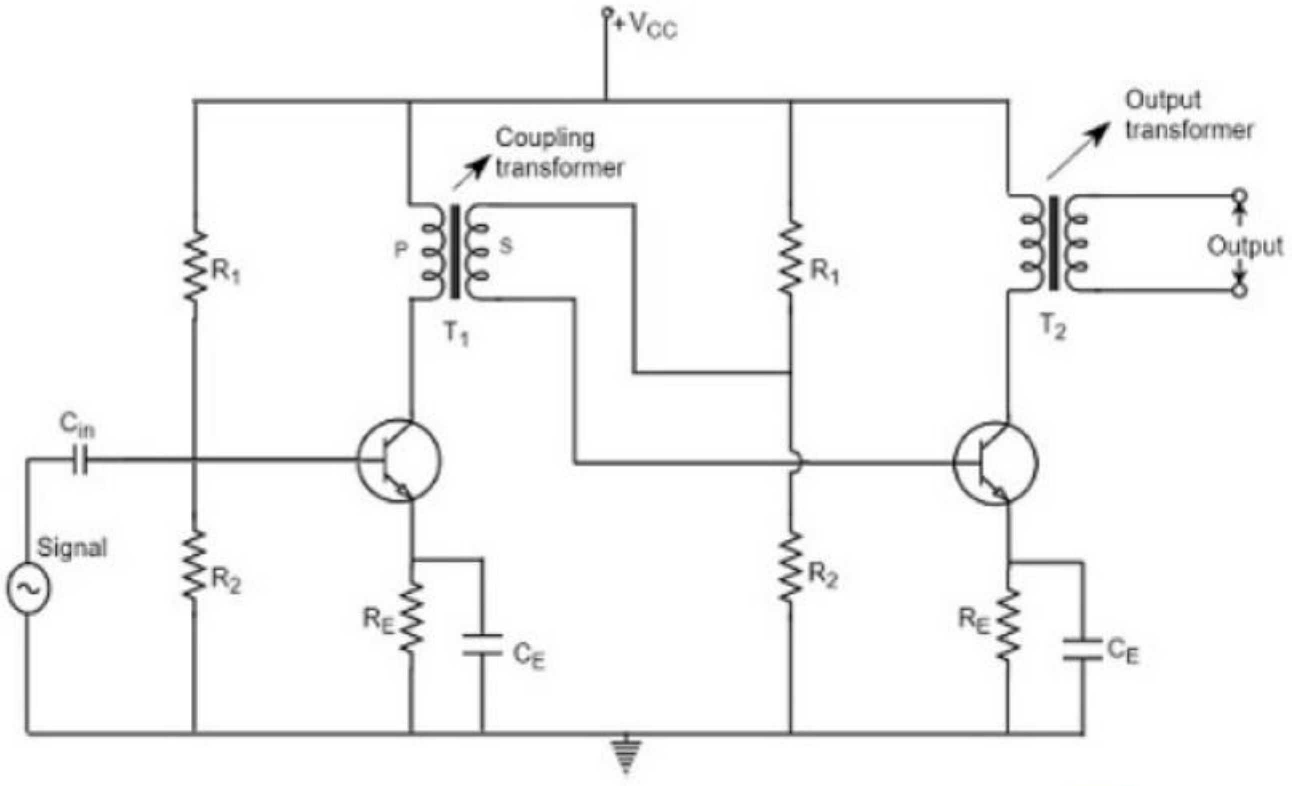
Coupling Methods in Multistage Amplifiers

3) Transformer coupling

- The loading effect can be reduced by replacing the resistance Rc with a transformer.
- The primary winding of the transformer is connected between collector and dc supply and the secondary winding is connected to the load.



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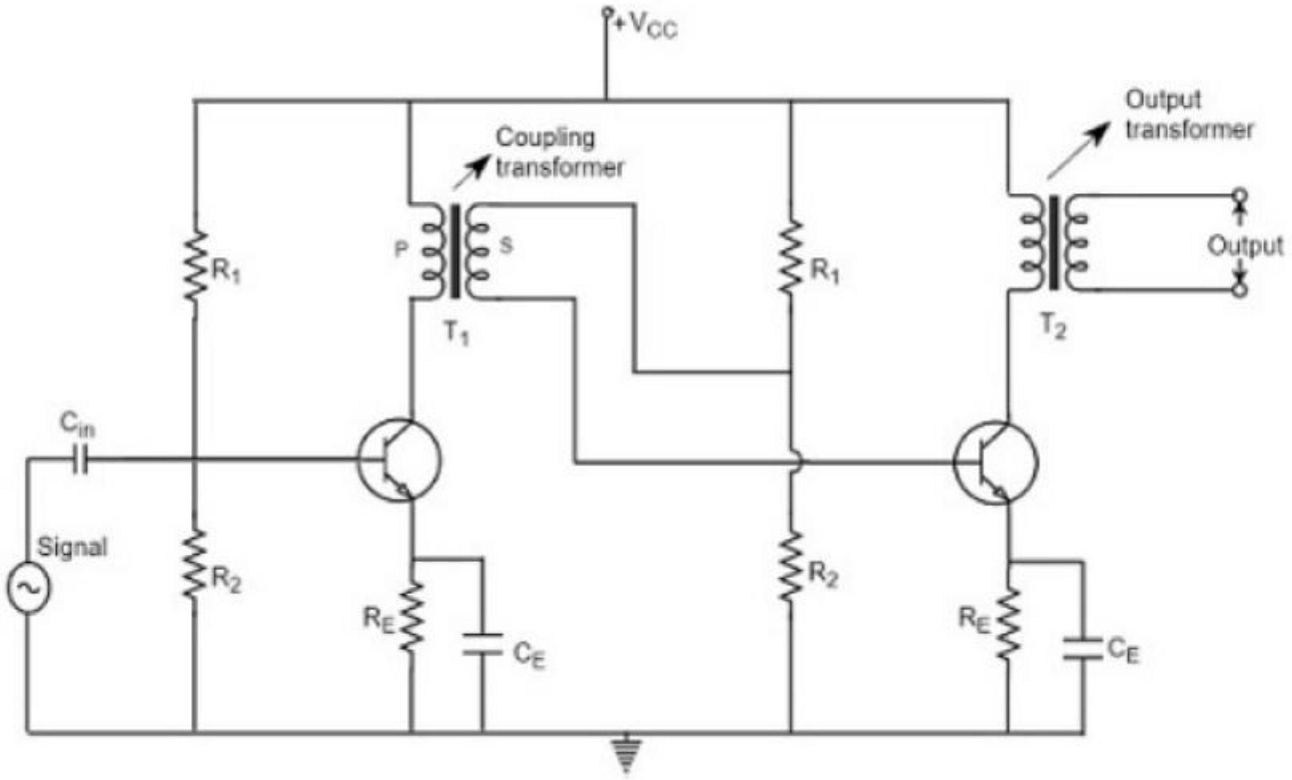
Coupling Methods in Multistage Amplifiers

3) Transformer coupling

- **By proper selection of the turns ratio of the transformer, impedance matching between the low input impedance of a stage (or load) with the output impedance of the previous stage can be achieved.**



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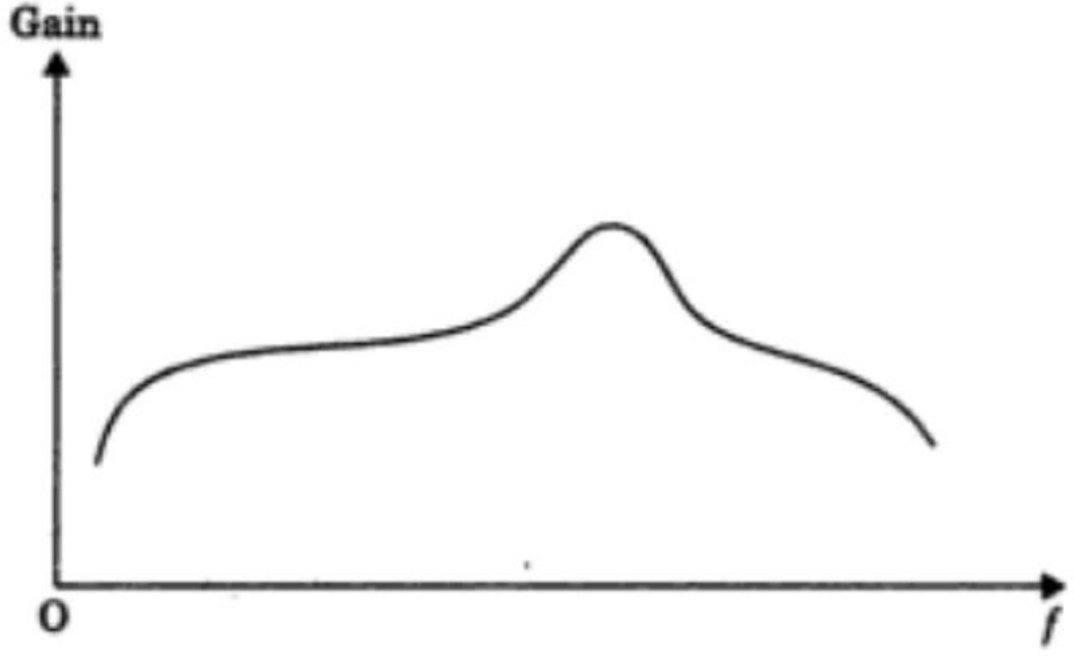
Coupling Methods in Multistage Amplifiers

3) Transformer coupling

- **The frequency response of a transformer coupled amplifier is shown in figure.**



Frequency response of a transformer coupled amplifier.

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Coupling Methods in Multistage Amplifiers

3) Transformer coupling

- **Applications**
  - It is mostly used for impedance matching.
  - The transformer coupling is used for amplifying radio frequency (RF) signals ($>$ 20 KHz).
  - The most important application of transformer coupling is in the last stage of a system to provide impedance matching.

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Coupling Methods in Multistage Amplifiers

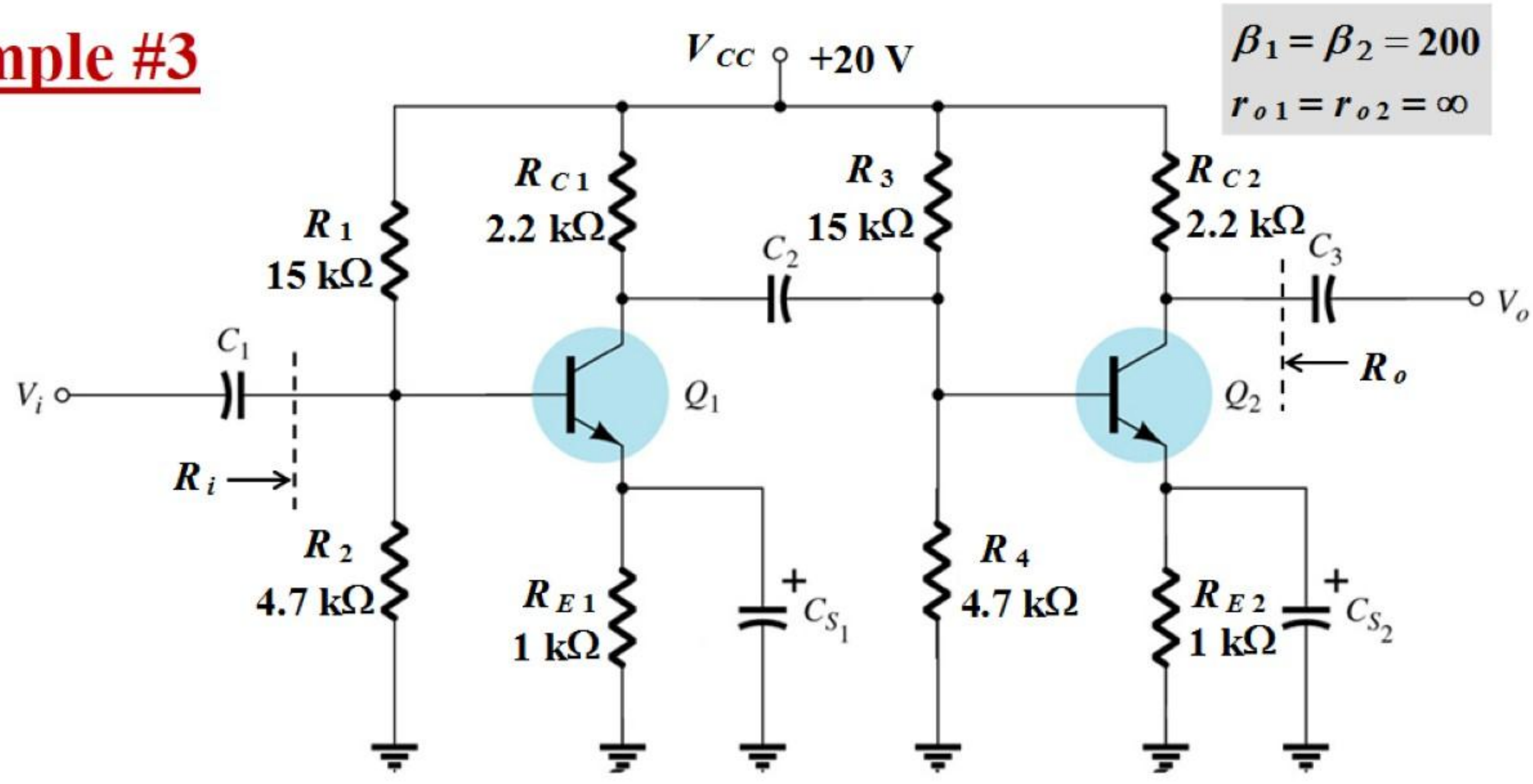
3) Transformer coupling

➢ Disadvantages

- ➢ It has a poor frequency response.
- ➢ The size of the transformer becomes very bulky.
- ➢ The cost is very high.

Characteristic	Capacitive coupling	Direct coupling	Transformer Coupling
Use	Voltage amplification	Amplifying extremely low frequency	Power amplification
Frequency response	Excellent in audio frequency (AF)	Best	Poor
Impedance matching	Not good	Good	Excellent
Weight & Space	Less	Least	More
Cost	Less	Least	More

Example #3



Draw the AC equivalent circuit and calculate A_v, R_i and R_o.

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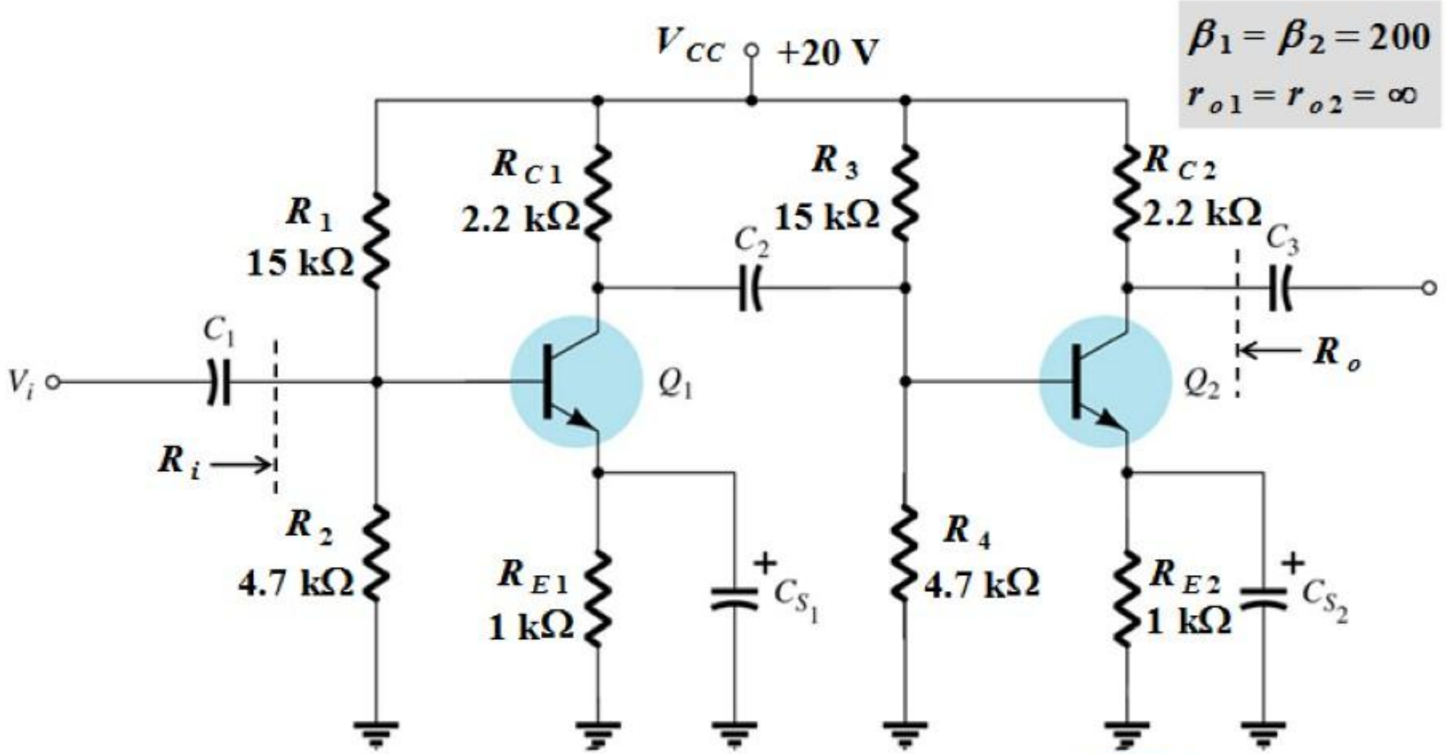
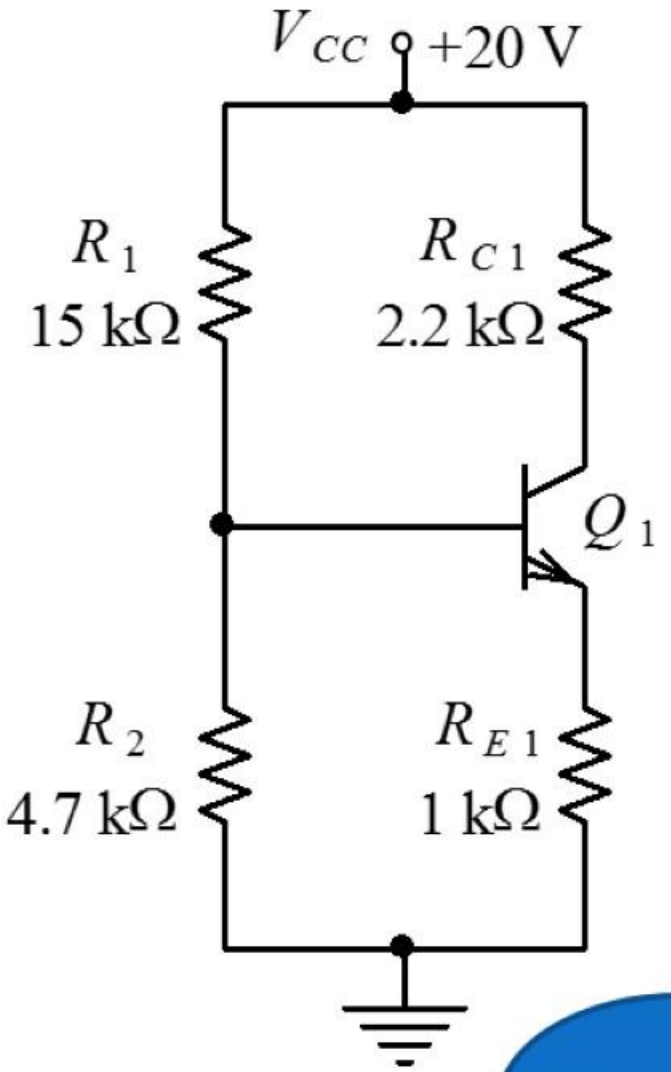
Solution

DC analysis

The circuit under DC condition (stage 1 and stage 2 are identical)





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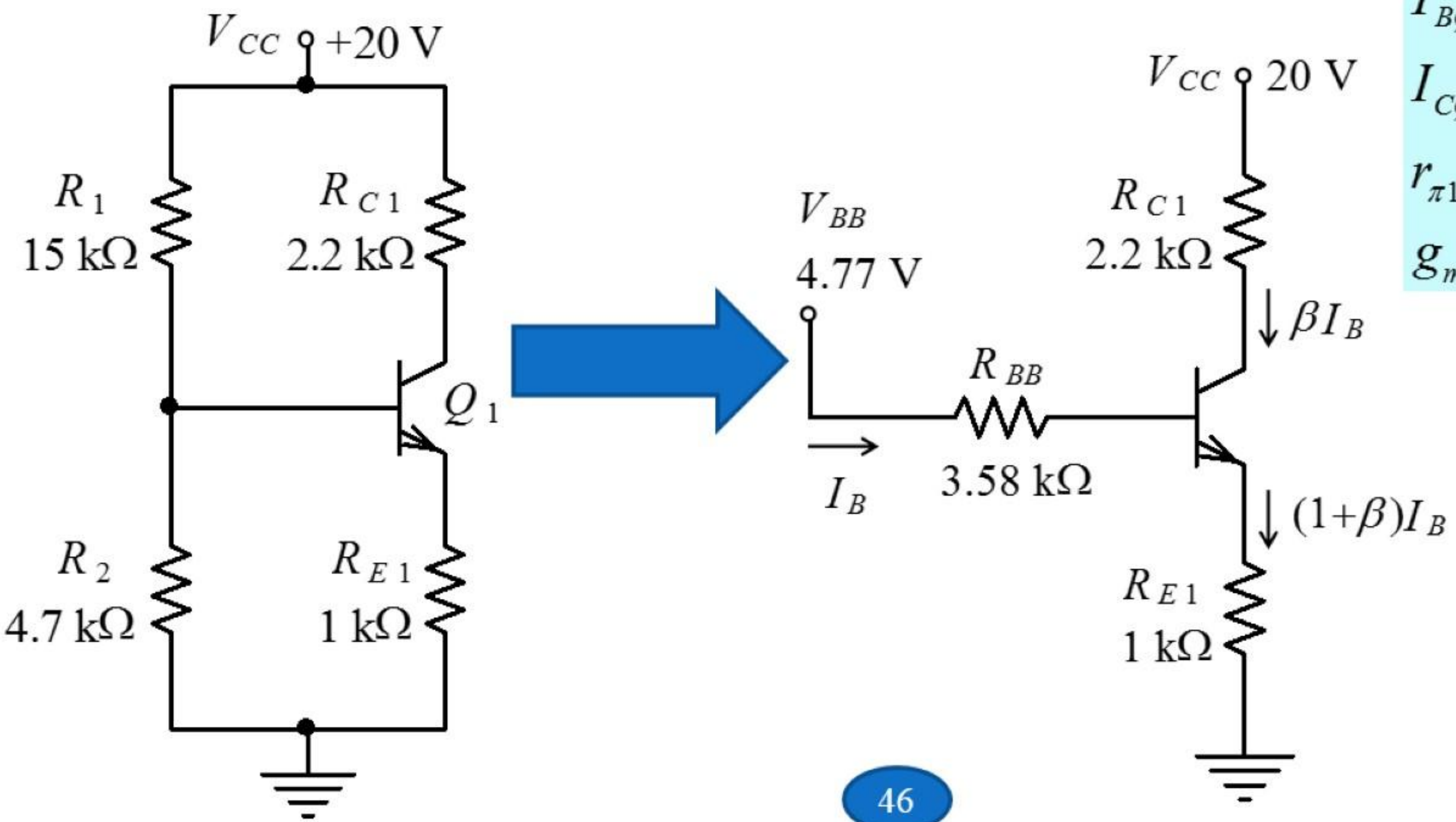
Applying Thevenin's theorem, the circuit becomes;



$$I_{BQ1} = I_{BQ2} = 19.89\,\mu\text{A}$$
$$I_{CQ1} = I_{CQ2} = 3.979\,\text{mA}$$
$$r_{\pi 1} = r_{\pi 2} = 1.307\,\text{k}\Omega$$
$$g_{m1} = g_{m2} = 0.153\,\text{A/V}$$

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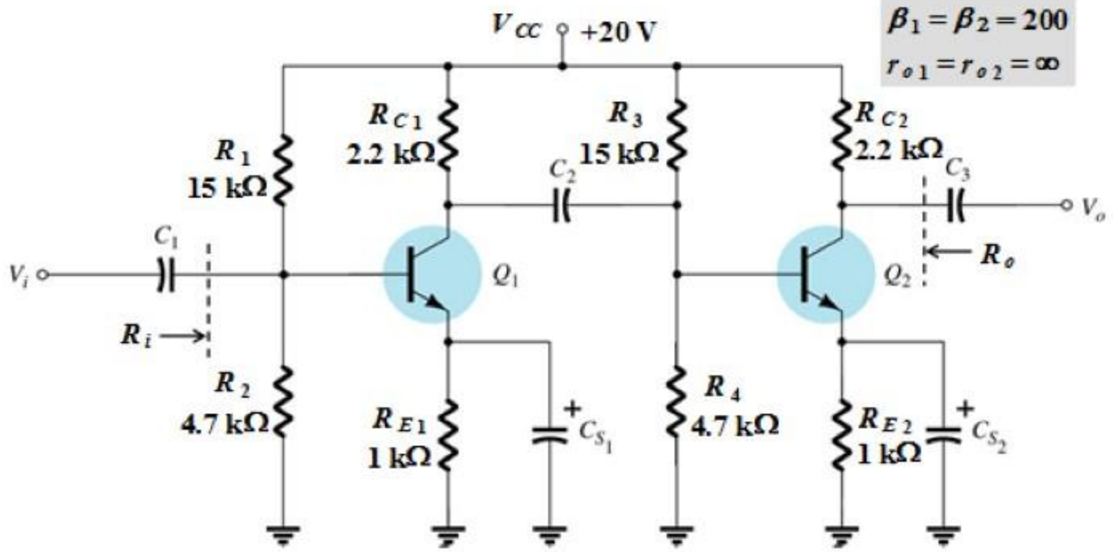
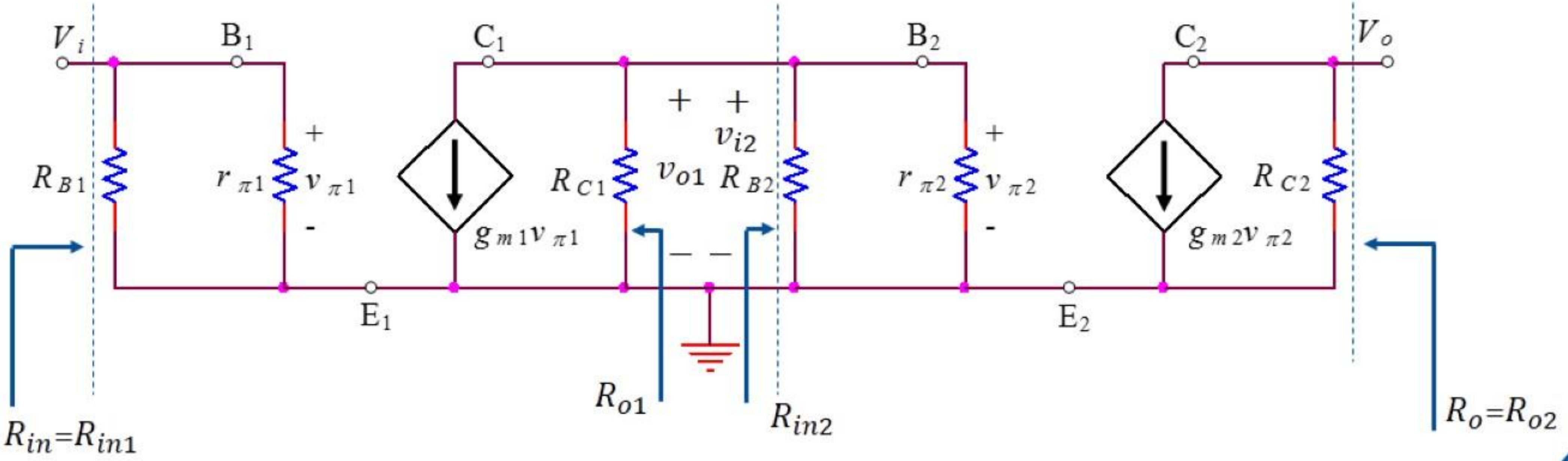
AC analysis

The small-signal equivalent circuit (mid-band);





$$R_{B1} = R_1 \,//\, R_2 \qquad R_{B2} = R_3 \,//\, R_4$$

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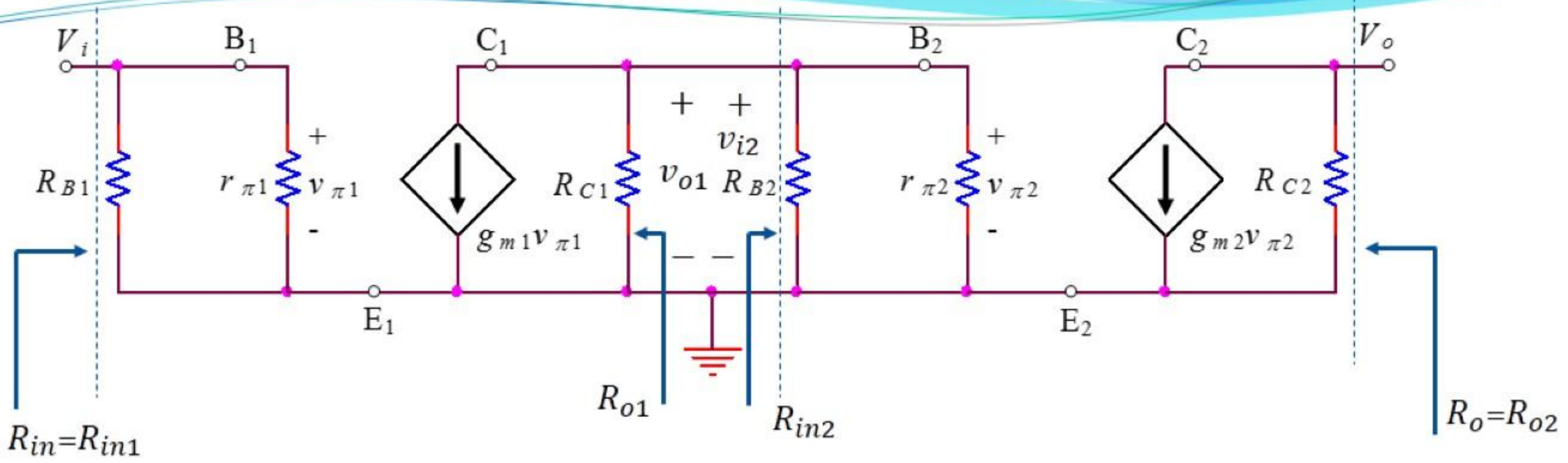

The input resistance;

$$R_{in} = R_{in1} = R_{B1} // r_{\pi 1} = 3.579 // 1.307 = 0.957 \text{ k}\Omega$$

The output resistance;

$$R_o = R_{o2} = R_{C2} = 2.2 \text{ k}\Omega$$

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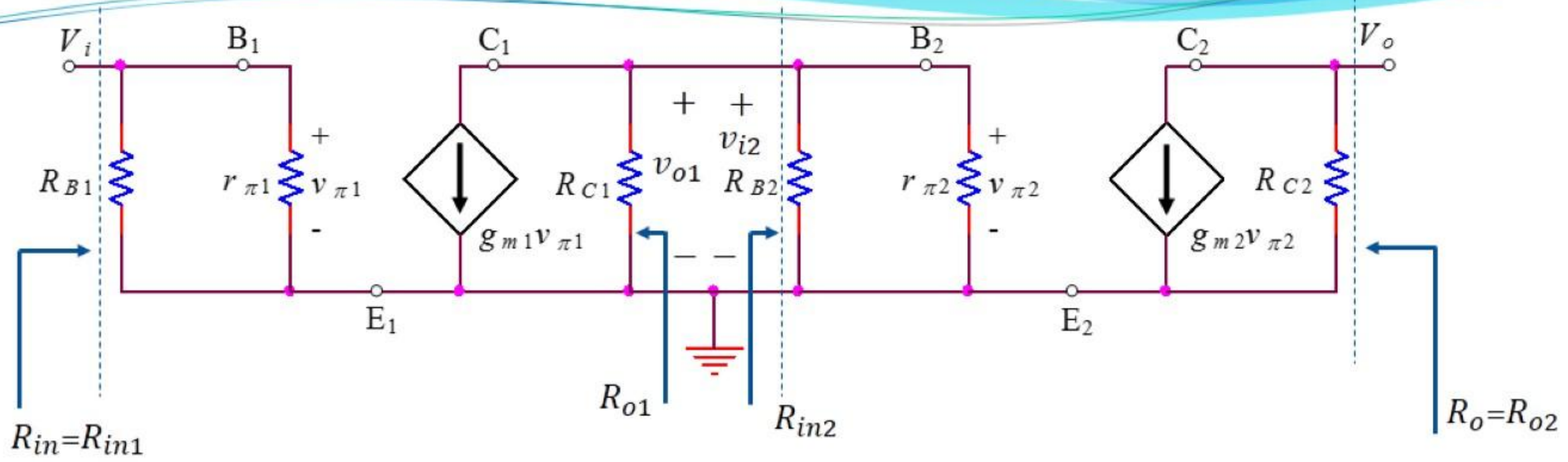

$$A_2 = \frac{v_o}{v_{i2}}$$

$$v_{i2} = v_{o1} = v_{\pi 2}$$

$$v_o = -g_{m2} v_{\pi 2} R_{C2}$$

$$A_2 = \frac{v_o}{v_{i2}} = \frac{v_o}{v_{\pi 2}} = -g_{m2} R_{C2}$$

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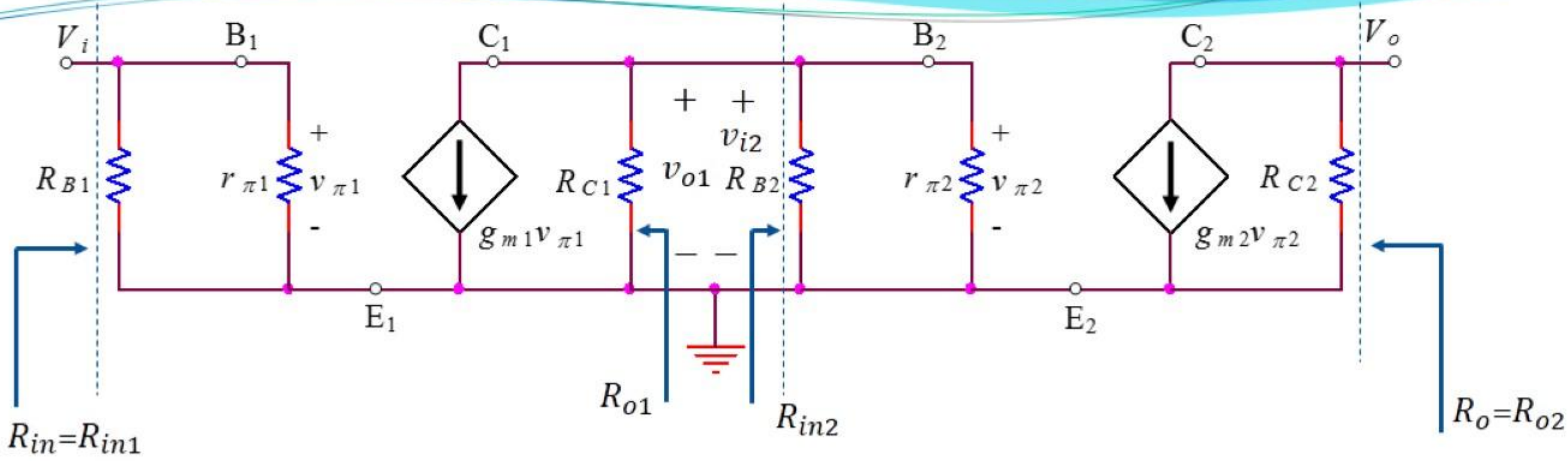

$$A_1 = \frac{v_{o1}}{v_i}$$

$$v_{o1} = v_{\pi 2}$$

$$v_i = v_{\pi 1}$$

$$v_{\pi 2} = -g_{m1} v_{\pi 1} \left(R_{C1} // R_{B2} // r_{\pi 2} \right)$$

$$A_1 = \frac{v_{o1}}{v_i} = \frac{v_{\pi 2}}{v_{\pi 1}} = -g_{m1} \left(R_{C1} // R_{B2} // r_{\pi 2} \right)$$

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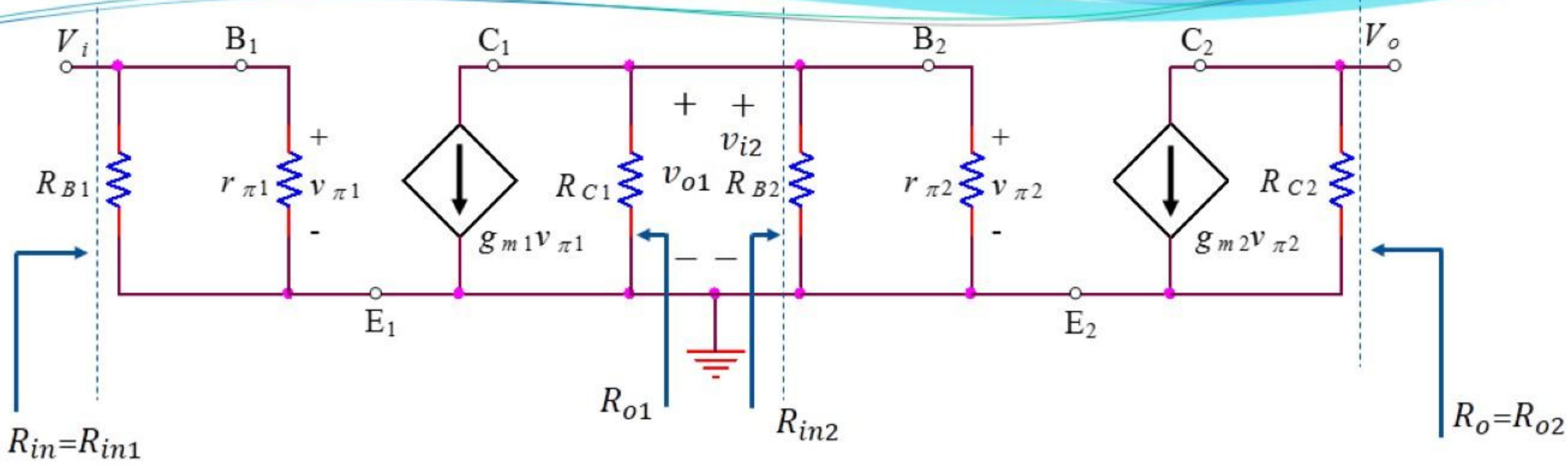

$$A = \frac{v_o}{v_i} = A_1 A_2$$

The small-signal voltage gain;

$$A = A_1 A_2 = g_{m1} g_{m2} R_{C2} \left(R_{C1} \,//\, R_{B2} \,//\, r_{\pi 2} \right)$$

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Substituting values;

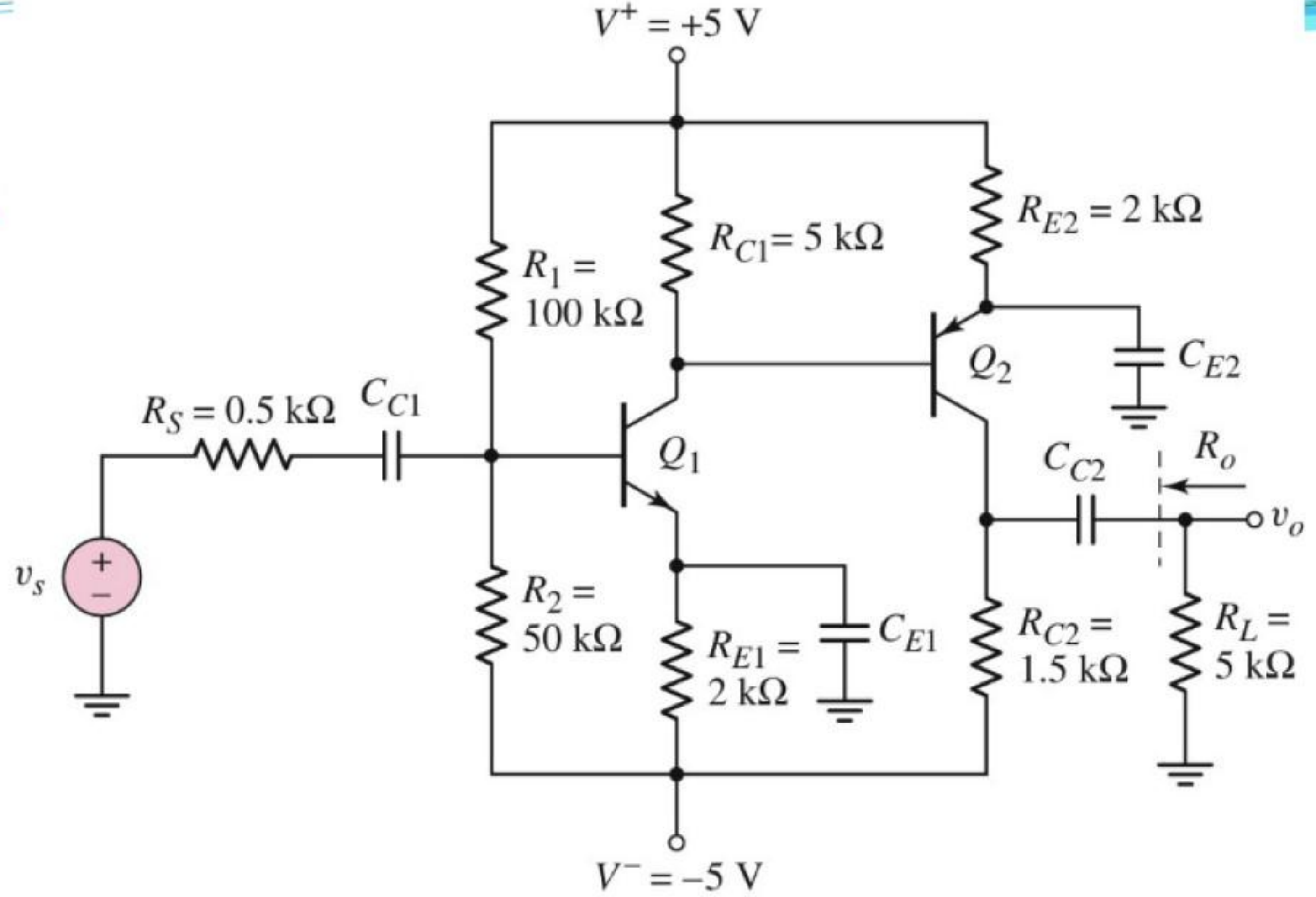
$$R_{B1} = R_{B2} = R_3 \,//\, R_4 = 15 \,//\, 4.7 = 3.579\,\mathrm{k\Omega}$$

$$R_{C1} \,//\, R_{B2} \,//\, r_{\pi 2} = 2.2 \,//\, 3.579 \,//\, 1.307 = 667\ \Omega$$

$$A = 0.153 \times 0.153 \times 2200 \times 667 = 34350\,\mathrm{V/V}$$

E. Sawires

Example #4

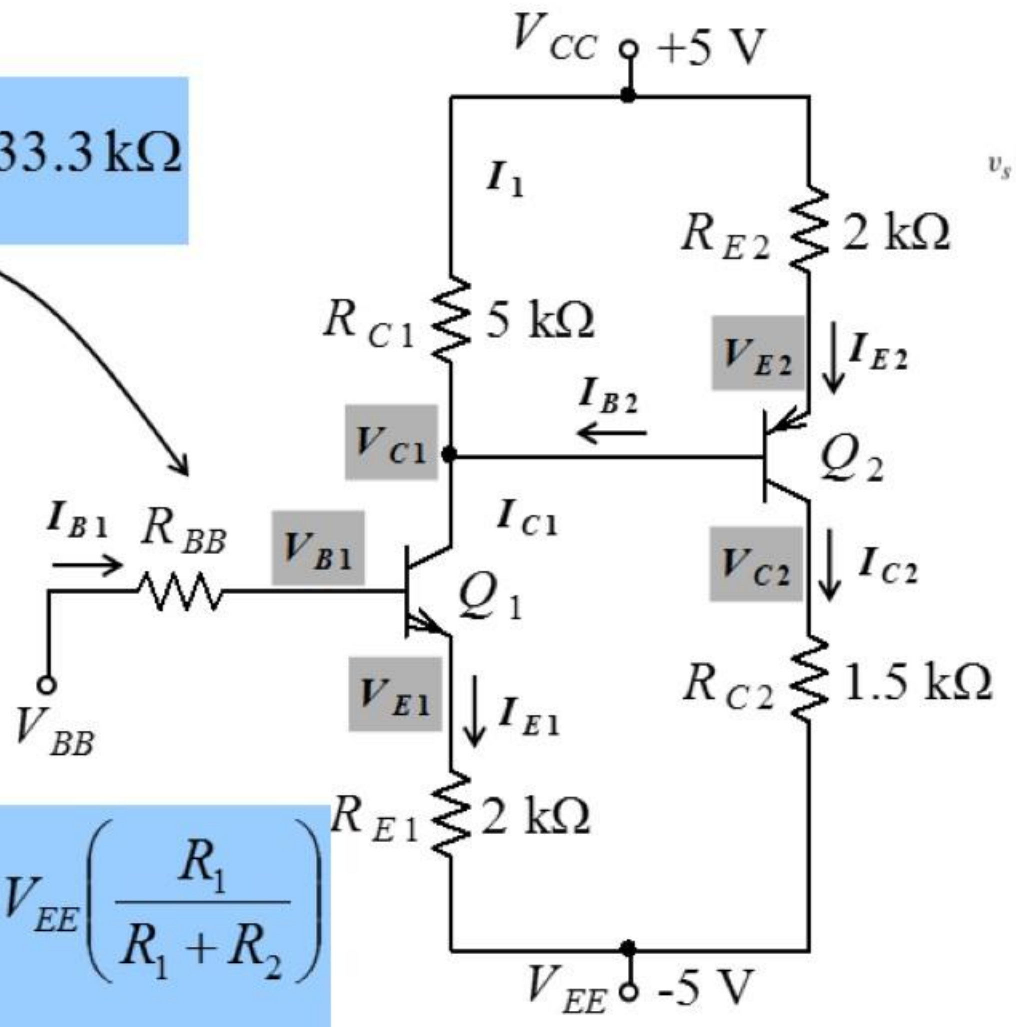


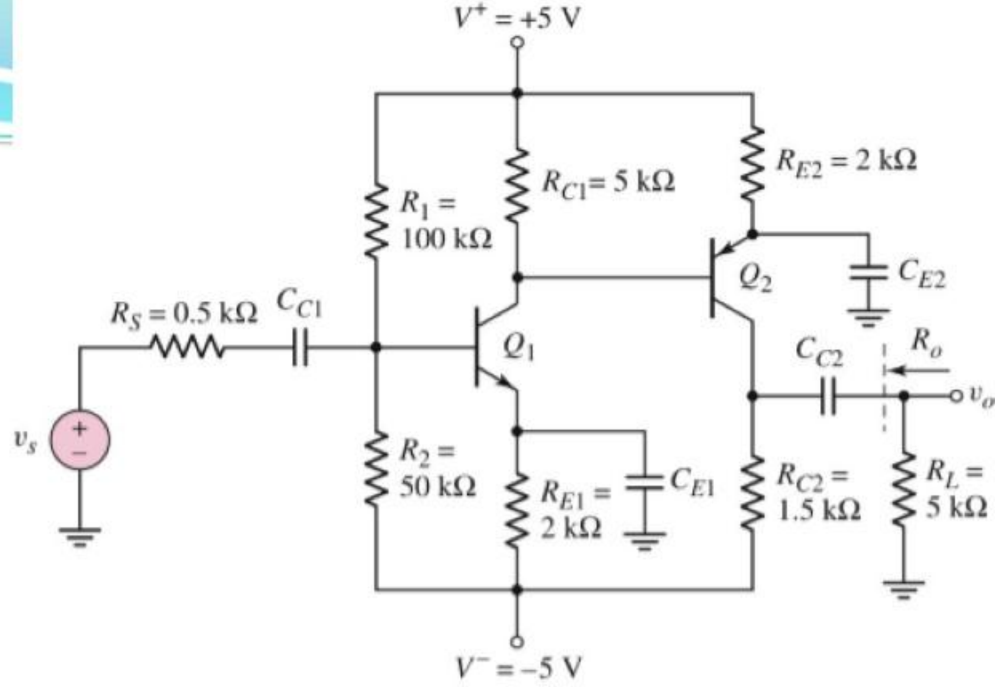
Assuming $\beta_1 = 170$, $\beta_2 = 150$ and $V_{BE(\text{ON})} = 0.7$ V, calculate the overall voltage gain G_v where; $G_v = \dfrac{v_o}{v_s}$

E. Sawires

DC analysis

$$R_{BB} = \frac{R_1 R_2}{R_1 + R_2} = 33.3\,\text{k}\Omega$$





$$V_{BB} = (V_{CC})\left(\frac{R_2}{R_1 + R_2}\right) + V_{EE}\left(\frac{R_1}{R_1 + R_2}\right)$$
$$= -1.667V$$

E. Sawires

The base-emitter loop of Q_1

$$V_{BB} - R_{BB}I_{B1} - V_{BE1} - R_{E1}I_{E1} - V_{EE} = 0$$

$$R_{BB}I_{B1} + (\beta_1 + 1)R_{E1}I_{B1} = V_{BB} - V_{EE} - V_{BE1}$$

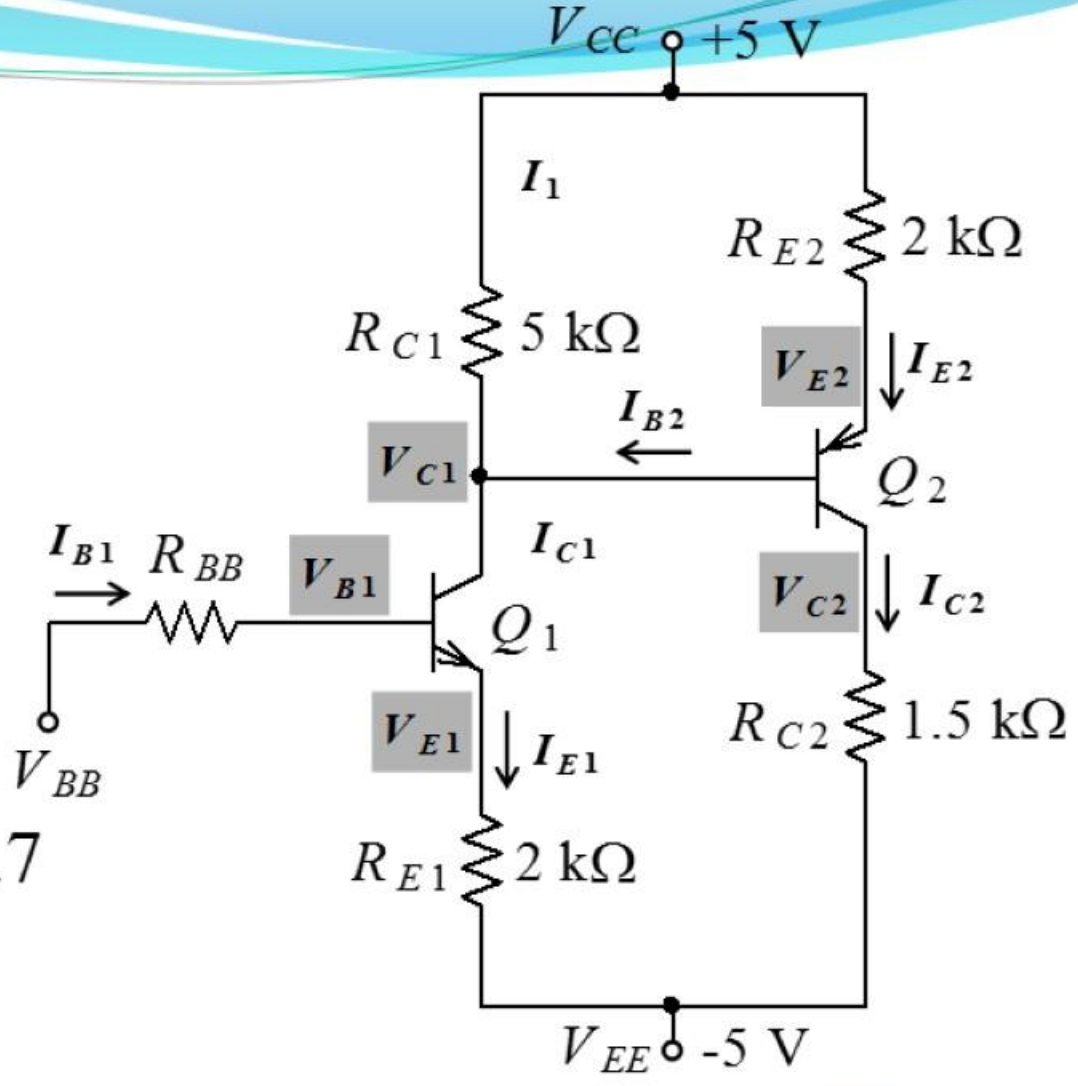
Substituting values;

$$33.3\times10^3 I_{B1} + (170+1)2\times10^3 I_{B1} = -1.667 + 5 - 0.7$$

$$I_{B1} = 7\ \mu\text{A}$$

$$I_{C1} = \beta_1 I_{B1} = 1.19\,\text{mA}$$

$$I_{E1} = (\beta_1 + 1)I_{B1} = 1.197\,\text{mA}$$



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For the R_{C1} – collector of Q_1 – base of Q_2 – R_{E2} loop

$$R_{E2}I_{E2}+V_{EB2}=R_{C1}I_1$$

$$I_1=I_{C1}-I_{B2}$$

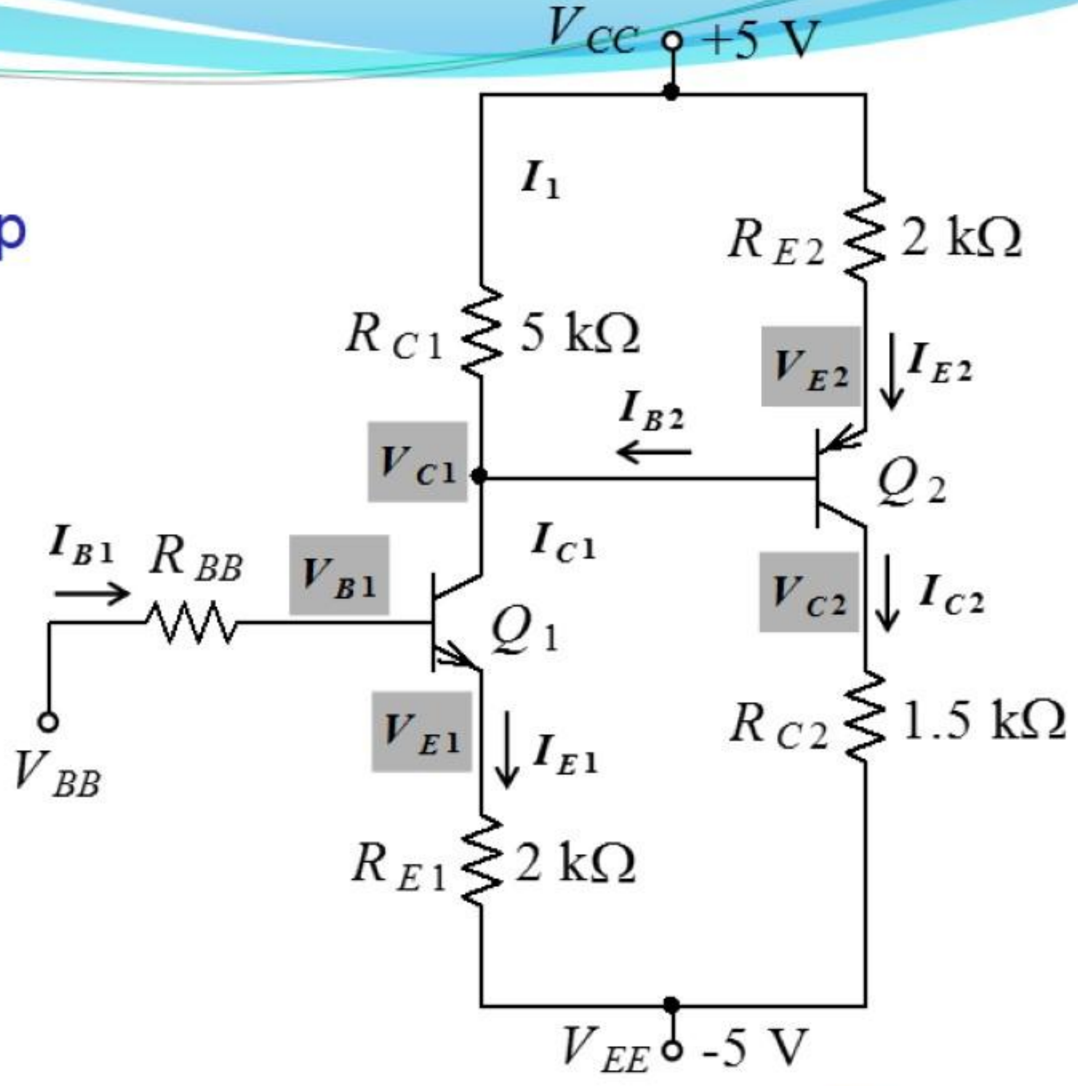
$$I_{E2}=(\beta_2+1)I_{B2}$$

$$(\beta_2+1)R_{E2}I_{B2}+V_{EB2}=R_{C1}(I_{C1}-I_{B2})$$

Substituting values;

$$(150+1)2\times10^3 I_{B2}+0.7=5\times10^3(1.19\times10^{-3}-I_{B2})$$

$$I_{B2}=17\ \mu\text{A}$$



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$$I_{C2} = \beta_2 I_{B2} = 2.565\,\text{mA}$$

$$I_{E2} = (\beta_2 + 1) I_{B2} = 2.582\,\text{mA}$$

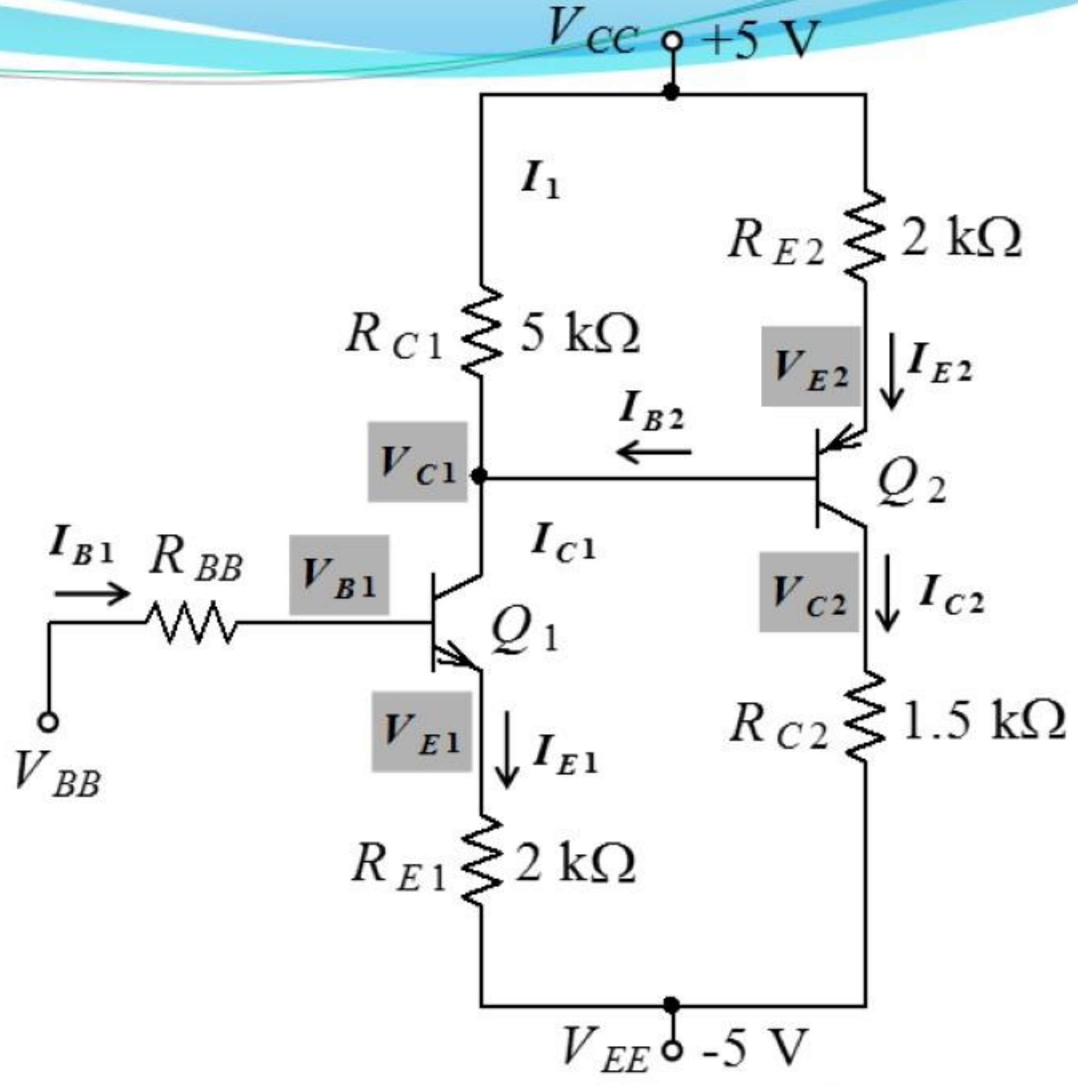
$$I_1 = I_{C1} - I_{B2} = 1.19 - 0.017 = 1.173\,\text{mA}$$

$$g_{m1} = \frac{I_{C1}}{V_T} = \frac{1.19}{26} = 45.77\,\text{mA/V}$$

$$r_{\pi 1} = \beta_1 \frac{V_T}{I_{C1}} = 170 \times \frac{26}{1.19} = 3714\,\Omega$$

$$g_{m2} = \frac{I_{C2}}{V_T} = \frac{2.565}{26} = 98.65\,\text{mA/V}$$

$$r_{\pi 2} = \beta_2 \frac{V_T}{I_{C2}} = 150 \times \frac{26}{2.565} = 1520\,\Omega$$



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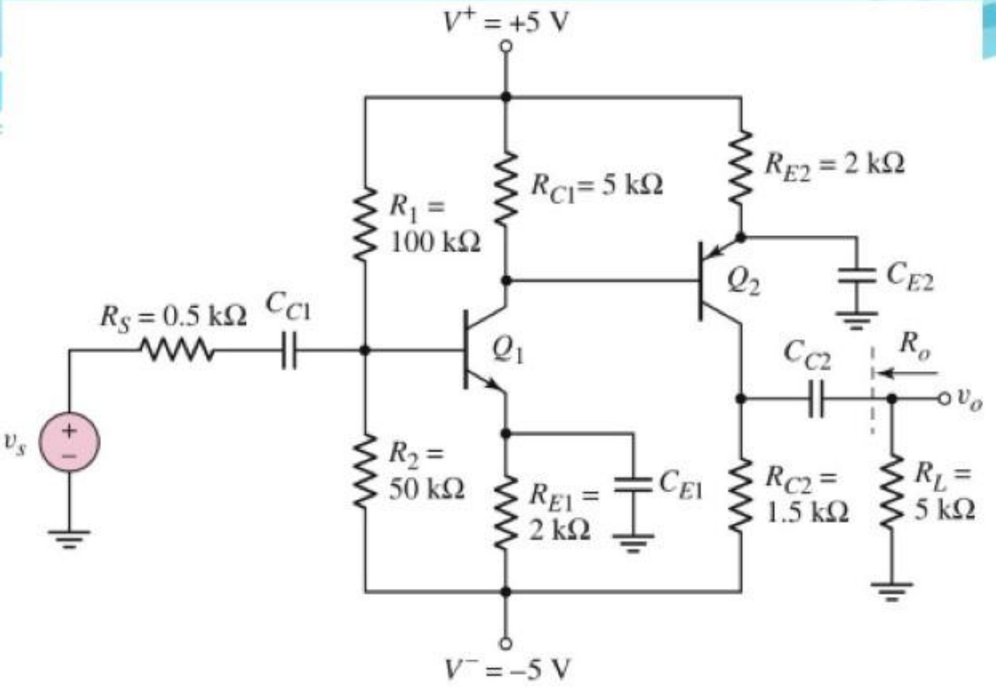
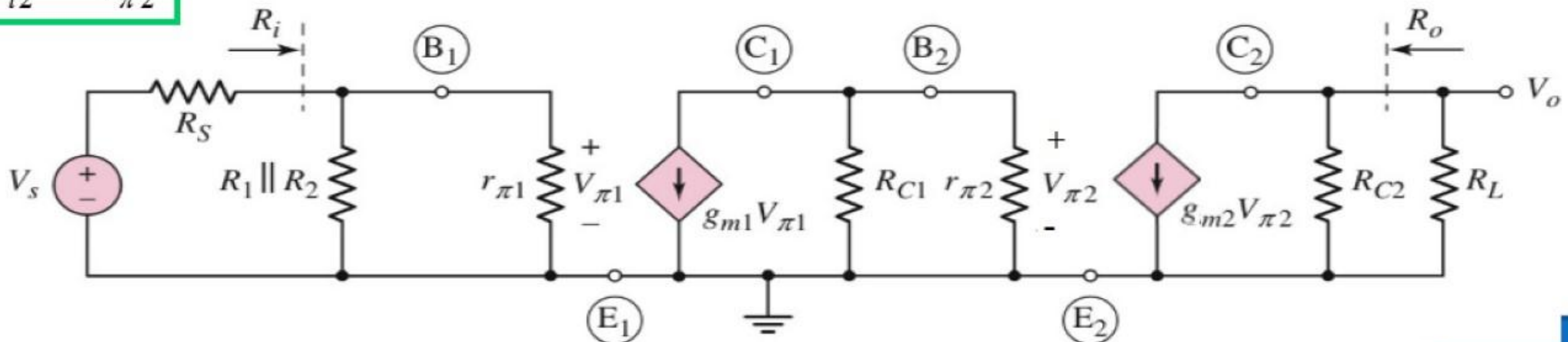
AC analysis

$$\boxed{A_1 = \frac{v_{o1}}{v_S} = \frac{v_{\pi 2}}{v_S}}$$

$$\boxed{A_2 = \frac{v_o}{v_{i2}} = \frac{v_o}{v_{\pi 2}}}$$





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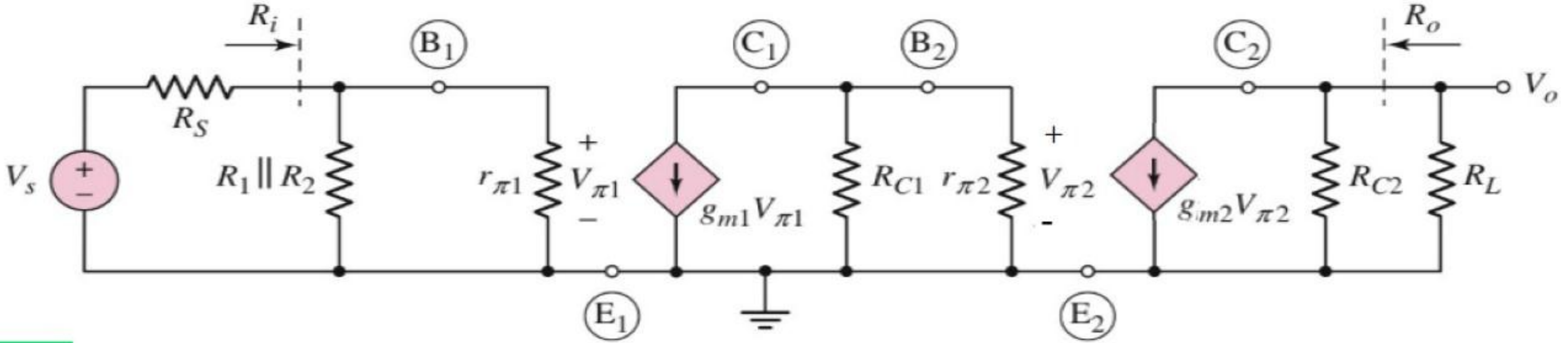

$$\boxed{A_1 = \frac{v_{o1}}{v_S} = \frac{v_{\pi 2}}{v_S}}$$

$$A_1 = \frac{v_{o1}}{v_S} = \frac{v_{\pi 2}}{v_s} = \frac{v_{\pi 2}}{v_{\pi 1}} \times \frac{v_{\pi 1}}{v_s}$$

$$v_{\pi 2} = -g_{m1} v_{\pi 1} \left(R_{C1} // r_{\pi 2}\right) \Longrightarrow \frac{v_{\pi 2}}{v_{\pi 1}} = -g_{m1}\left(R_{C1} // r_{\pi 2}\right)$$

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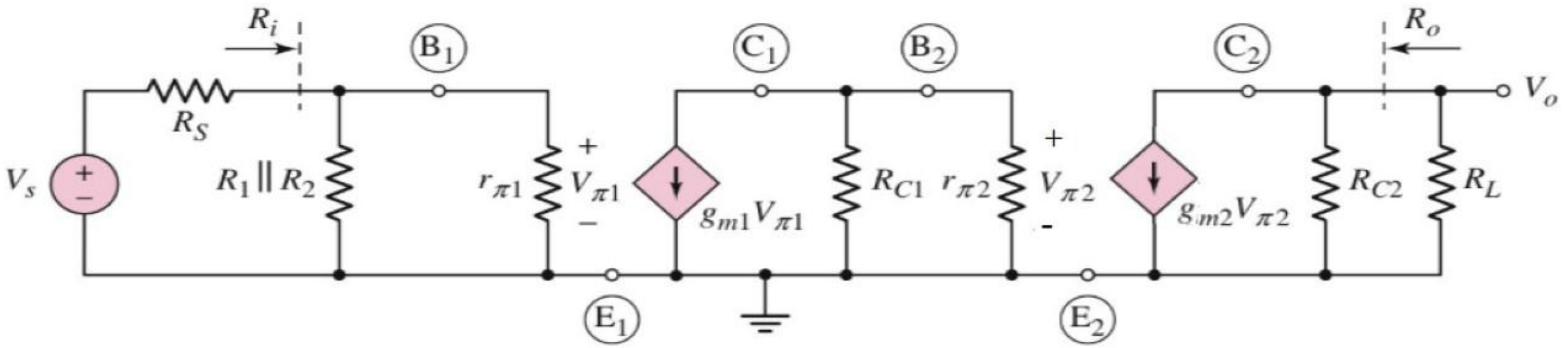

$$v_{\pi 1} = v_s \left(\frac{R_{in}}{R_S + R_{in}} \right) \qquad \Longrightarrow \qquad \frac{v_{\pi 1}}{v_s} = \frac{R_{in}}{R_S + R_{in}}$$

$$A_1 = \frac{v_{\pi 2}}{v_s} = \frac{v_{\pi 2}}{v_{\pi 1}} \times \frac{v_{\pi 1}}{v_s} = -g_{m1}\left(R_{C1} // r_{\pi 2}\right)\left(\frac{R_{in}}{R_S + R_{in}} \right)$$

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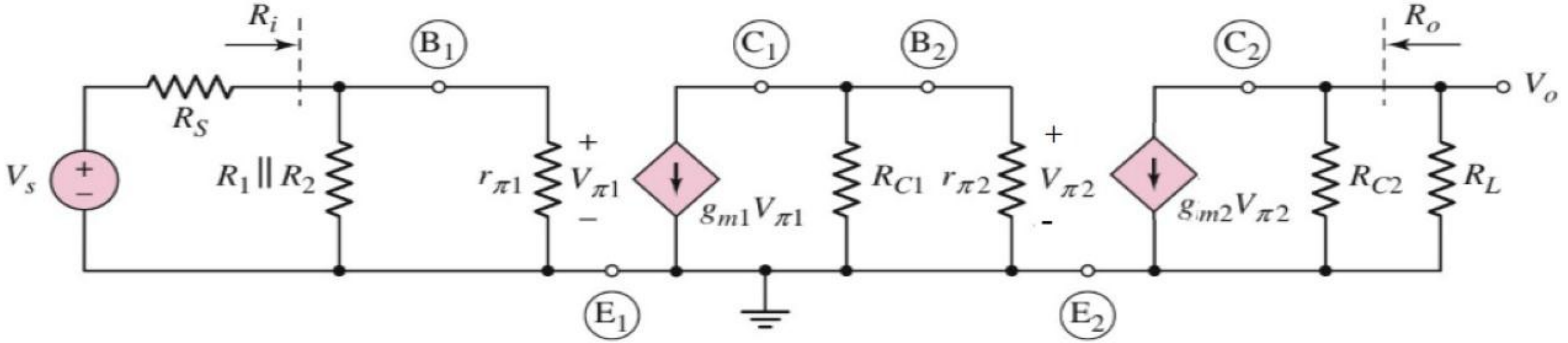

$$A_2 = \frac{v_o}{v_{\pi 2}}$$

$$v_o = -g_{m2} v_{\pi 2}\left(R_{C2} // R_L\right) \Longrightarrow A_2 = \frac{v_o}{v_{\pi 2}} = -g_{m2}\left(R_{C2} // R_L\right)$$

$$A = A_1 A_2 = -g_{m1}\left(R_{C1} // r_{\pi 2}\right)\left(\frac{R_{in}}{R_S + R_{in}}\right)\left[-g_{m2}\left(R_{C2} // R_L\right)\right]$$

$$A = g_{m1} g_{m2}\left(R_{C1} // r_{\pi 2}\right)\left(R_{C2} // R_L\right)\left(\frac{R_{in}}{R_S + R_{in}}\right)$$

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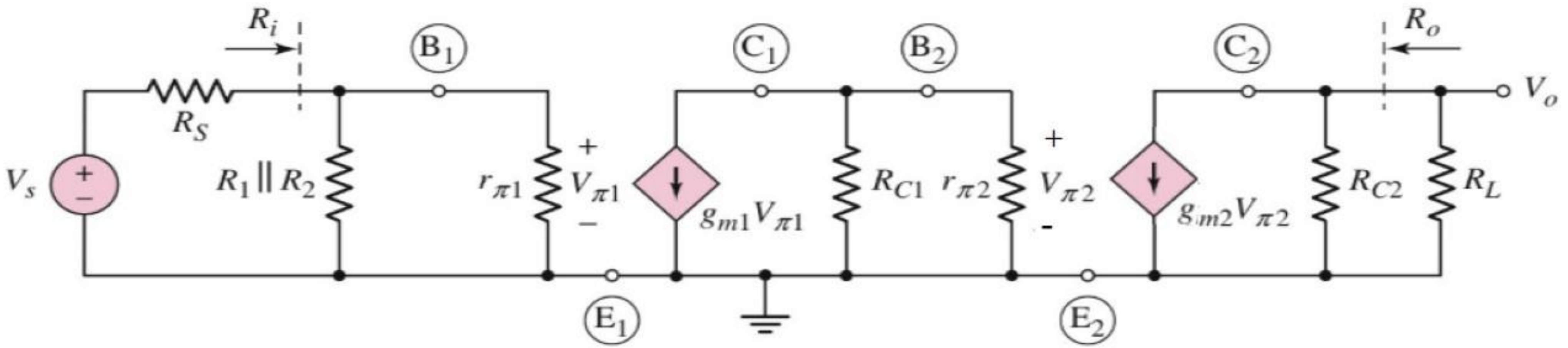

$$A = g_{m1} g_{m2} (R_{C1} // r_{\pi 2})(R_{C2} // R_L)\left(\frac{R_{in}}{R_S + R_{in}}\right)$$

$$= 45.77 \times 98.65 (5 // 1.52)(1.5 // 5)\left(\frac{3.342}{0.5 + 3.342}\right)$$

$$\boxed{A = 5286\,\text{V/V}}$$

$$R_{in} = R_{in1} = R_1 // R_2 // r_{\pi 1} = 100 // 50 // 3.714 = 3.342\,\text{k}\Omega$$

$$R_o = R_{o2} = R_{C2} = 1.5\,\text{k}\Omega$$

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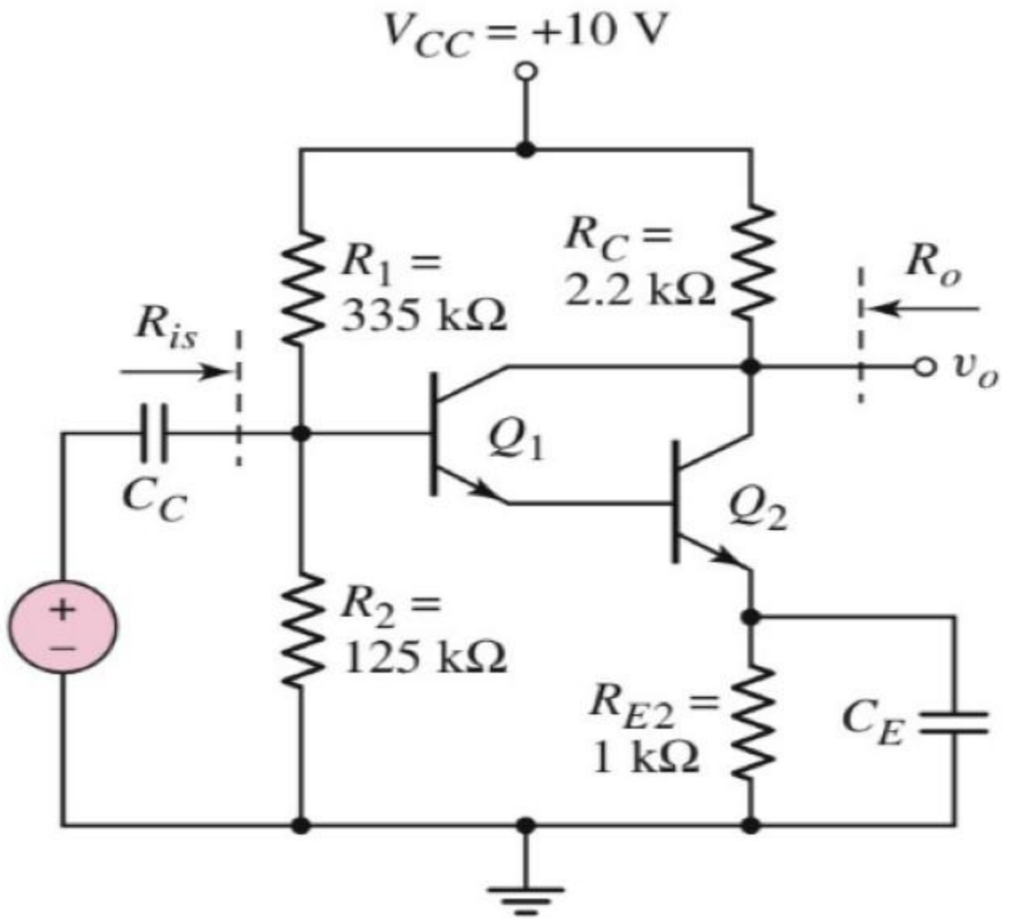
Example #5

- Determine the Q-point for Q_1 and Q_2, voltage gain v_o/v_s, , current gain, input resistance R_{is}, and output resistance R_o for the darlington configuration shown in Fig. Assuming $\beta_1 = \beta_2 = 100$, $V_{A1} = V_{A2} = \infty$, and $V_{BE1(ON)} = V_{BE2(ON)} = 0.7$ V.



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Example #5

$$\beta_1 = \beta_2 = 100$$

$$V_{A1} = V_{A2} = \infty$$

$$V_{BE1} = V_{BE2} = 0.7\ \text{V}$$

Determine the;

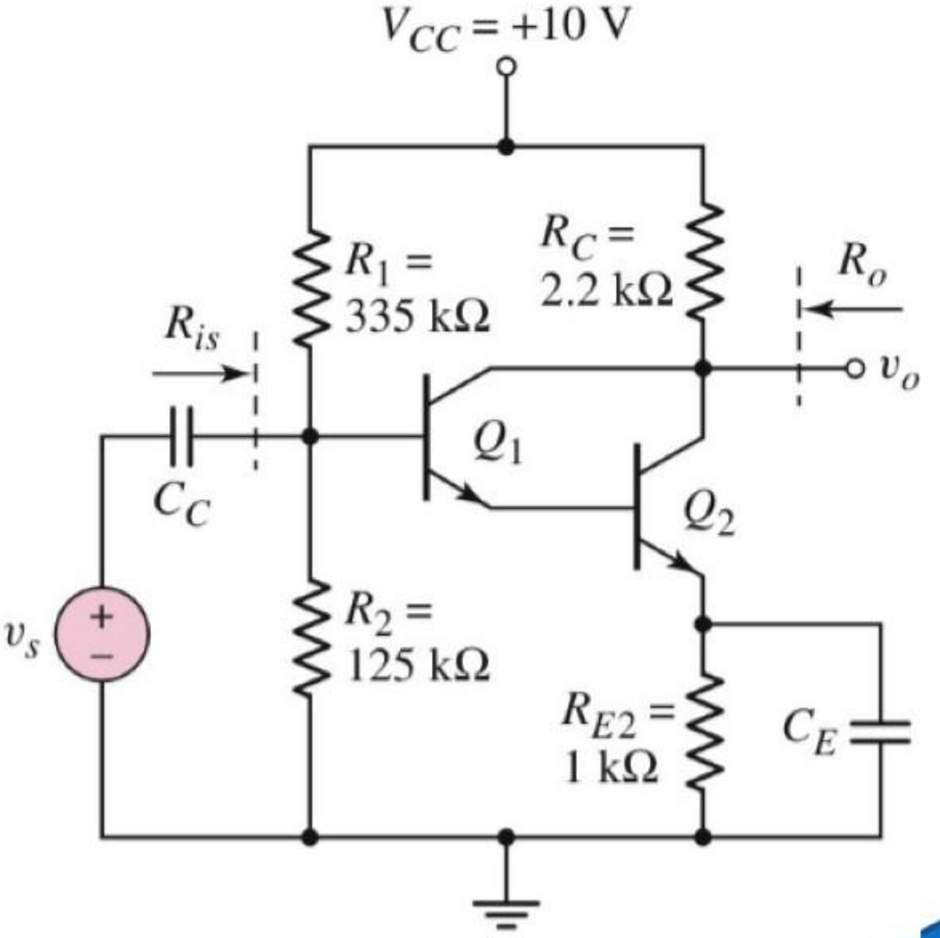
(a) Q-point for Q_1 and Q_2;

(b) voltage gain v_o/v_s;

(c) current gain;

(d) input resistance R_{is};

(e) output resistance R_o



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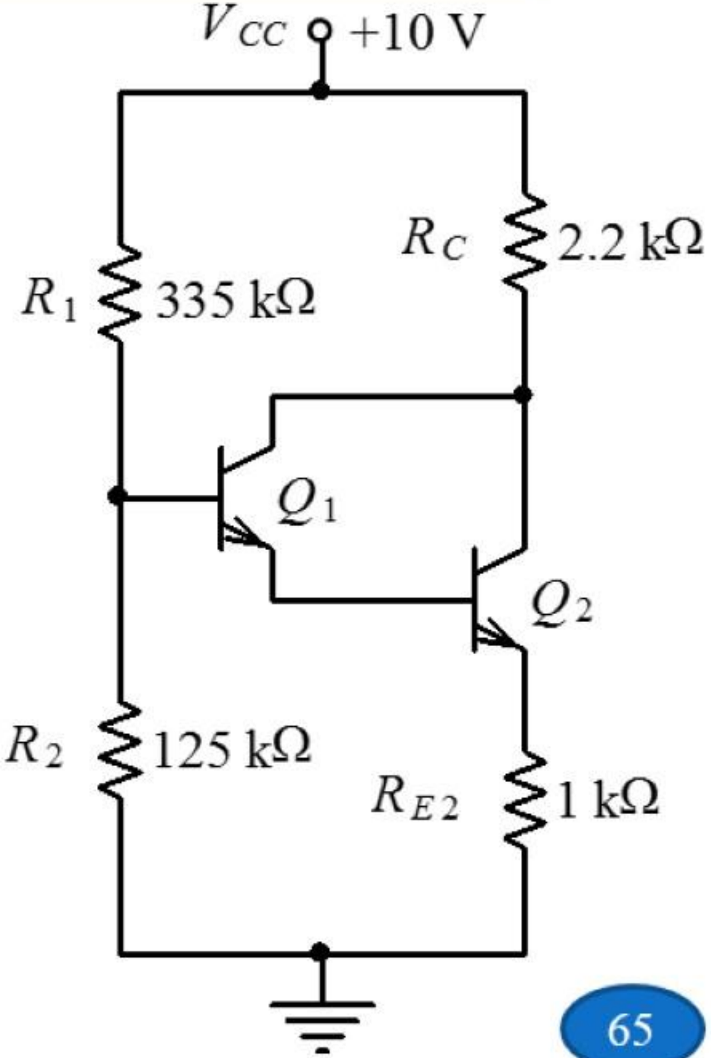
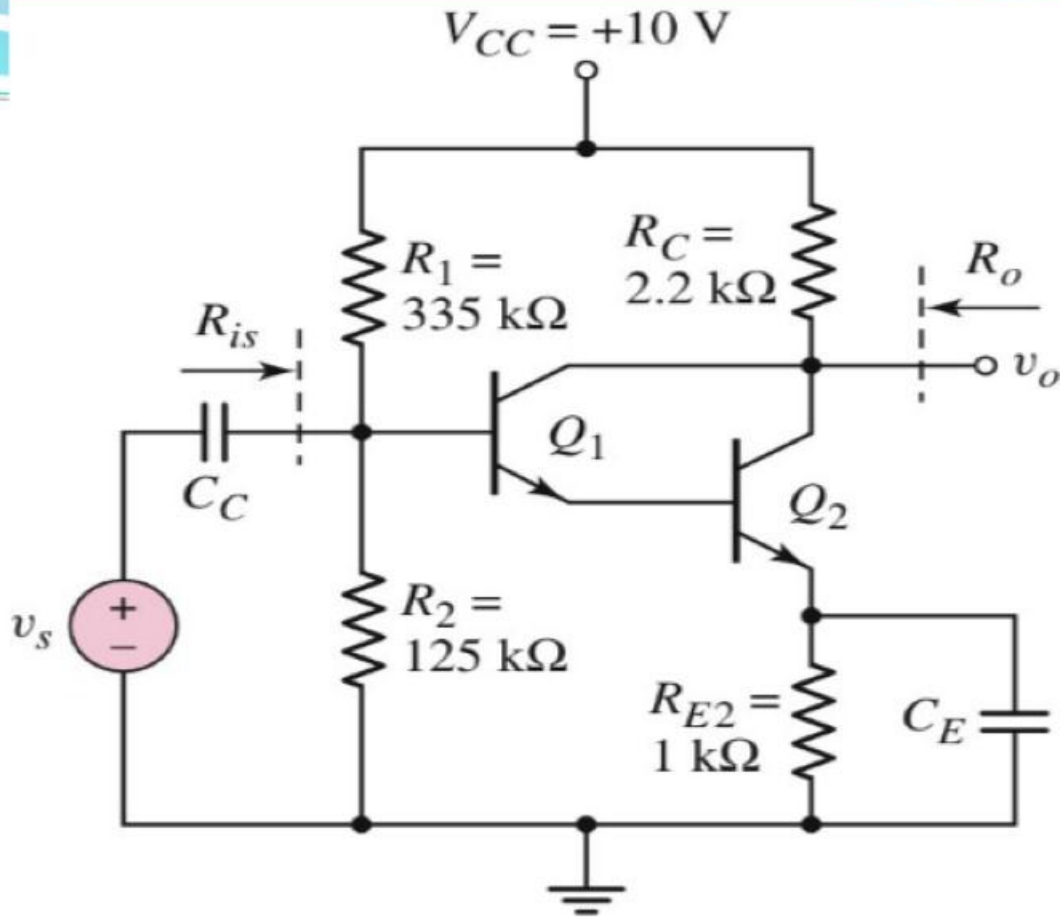
(a) Determination of Q-points

DC analysis





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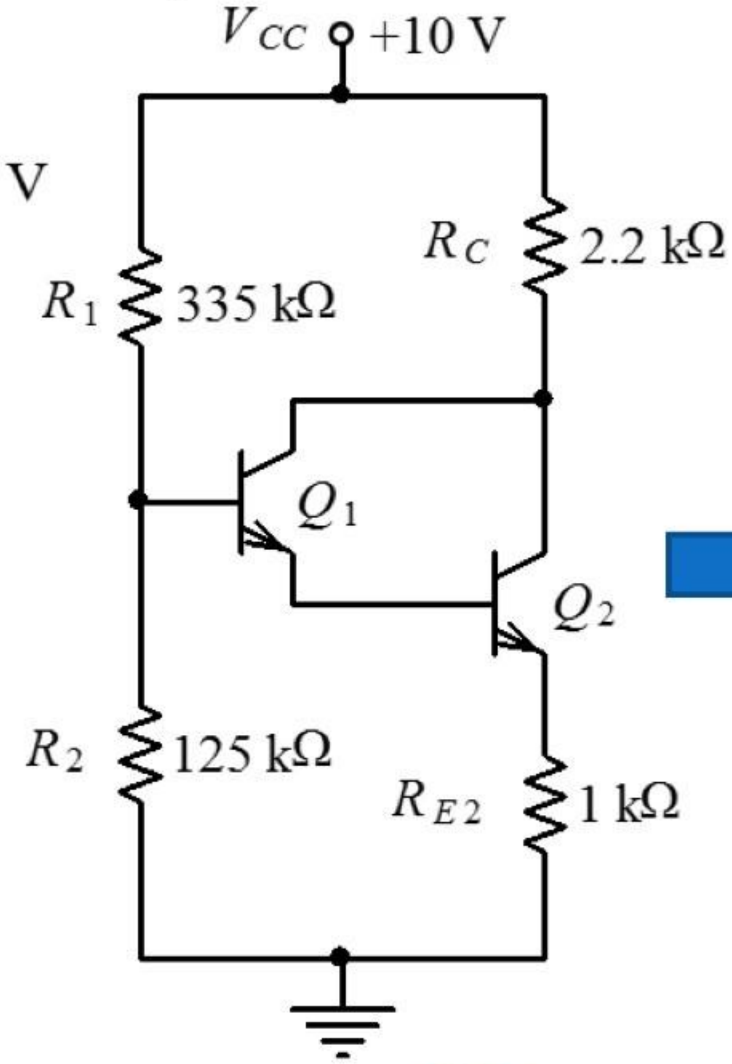
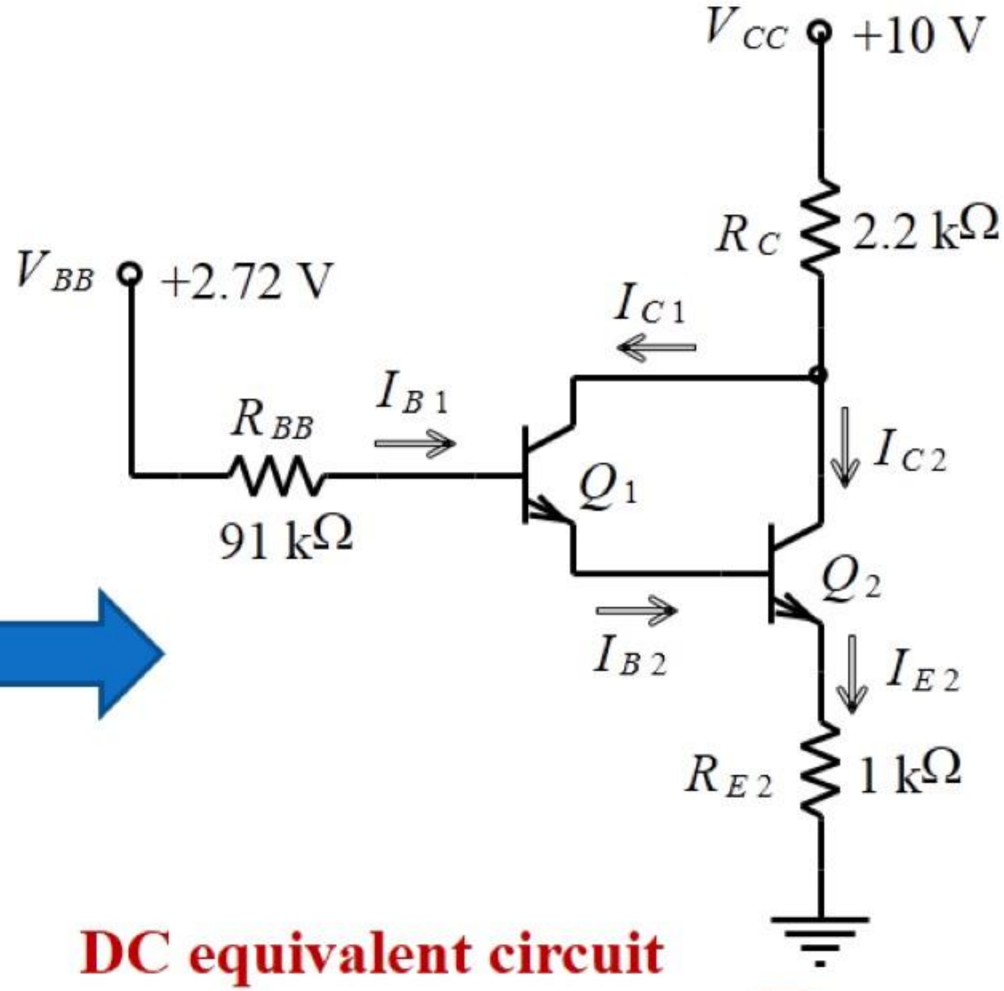
Using Thevenin's theorem;

$$V_{BB} = V_{CC}\left(\frac{R_2}{R_1 + R_2}\right) = 2.72\ \text{V}$$

$$R_{BB} = \frac{R_1 R_2}{R_1 + R_2} = 91\,\text{k}\Omega$$





DC equivalent circuit

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$$I_{B2} = I_{E1} = (\beta+1)I_{B1}$$

$$I_{E2} = (\beta+1)I_{B2} = (\beta+1)^2 I_{B1}$$

$$R_{BB}I_{B1} + 2V_{BE} + R_{E2}(\beta+1)^2 I_{B1} = V_{BB}$$

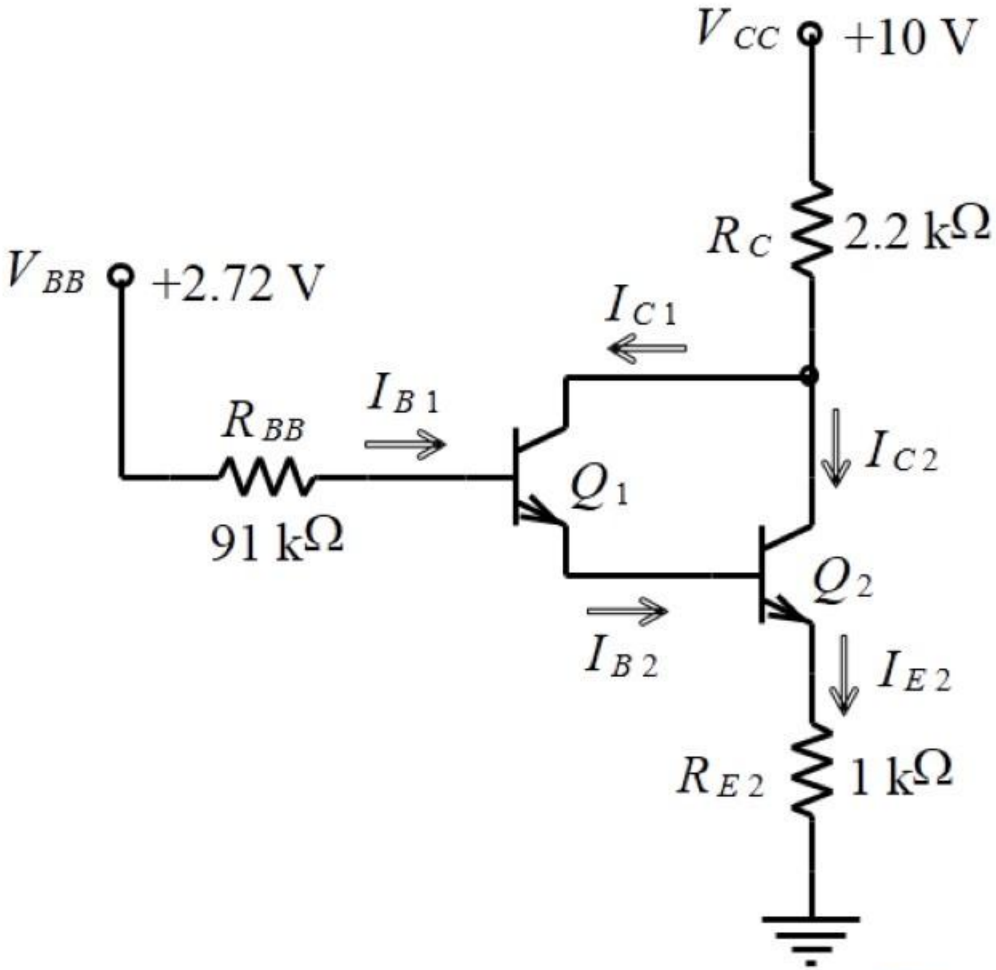
$$91\text{k}I_{B1} + 2\times0.7 + 1\text{k}(100+1)^2 I_{B1} = 2.72$$

$$I_{B1} = \frac{1.32}{10292}\times10^{-3} = 0.128\ \mu\text{A}$$

$$I_{C1} = 12.8\,\mu\text{A}$$

$$I_{E1} = I_{B2} = 12.93\,\mu\text{A}$$

$$I_{C2} = 1.293\ \text{mA}$$



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$$I_{E2} = 1.3\,\text{mA}$$

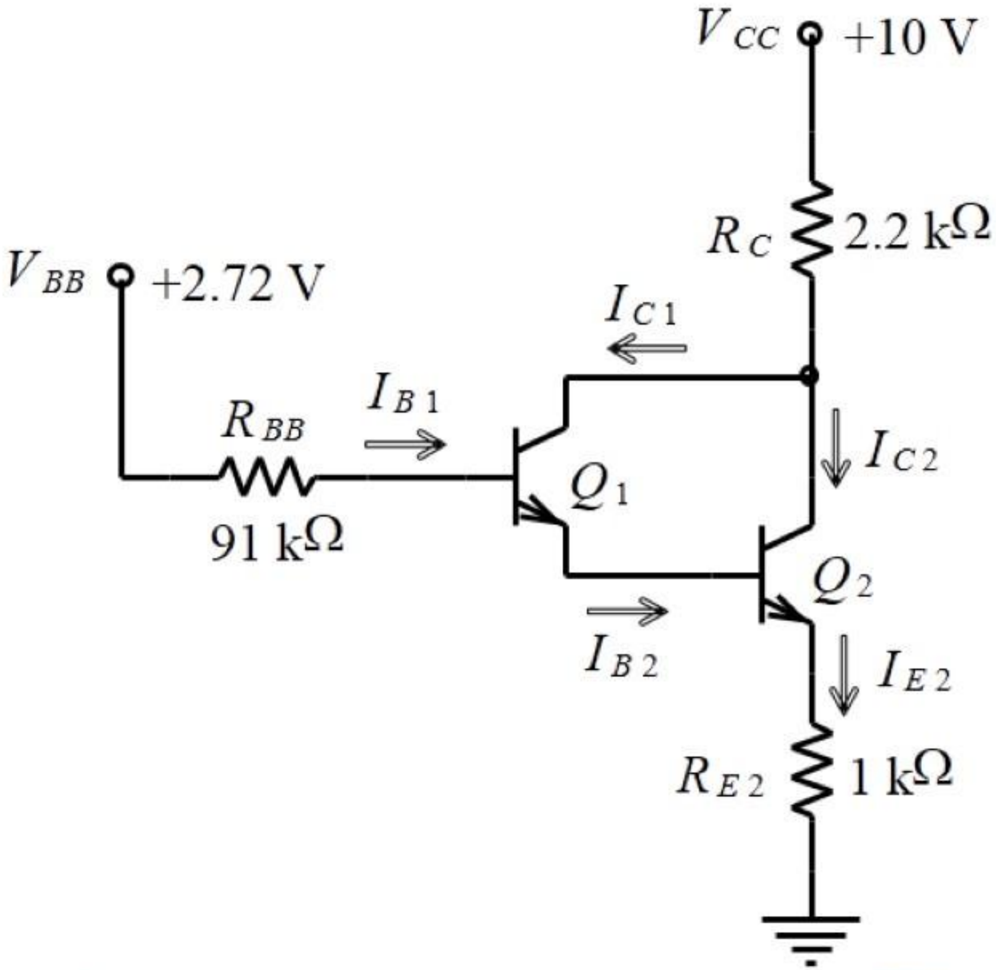
$$V_{E2} = 1.3 \times 1 = 1.3\,\text{V}$$

$$V_{E1} = 1.3 + 0.7 = 2\,\text{V}$$

$$V_{C1} = V_{C2} = 10 - 2.2(1.293 + 0.0128) = 7.127\,\text{V}$$

$$V_{CE1} = V_{C1} - V_{E1} = 7.127 - 2 = 5.127\,\text{V}$$

$$V_{CE2} = V_{C2} - V_{E2} = 7.127 - 1.3 = 5.827\,\text{V}$$



(a) The Q-points are;

Q_1: $I_{CQ1} = 12.8\,\mu\text{A}$; $V_{CEQ1} = 5.127\,\text{V}$
Q_2 : $I_{CQ2} = 1.293\,\text{mA}$; $V_{CEQ2} = 5.827\,\text{V}$

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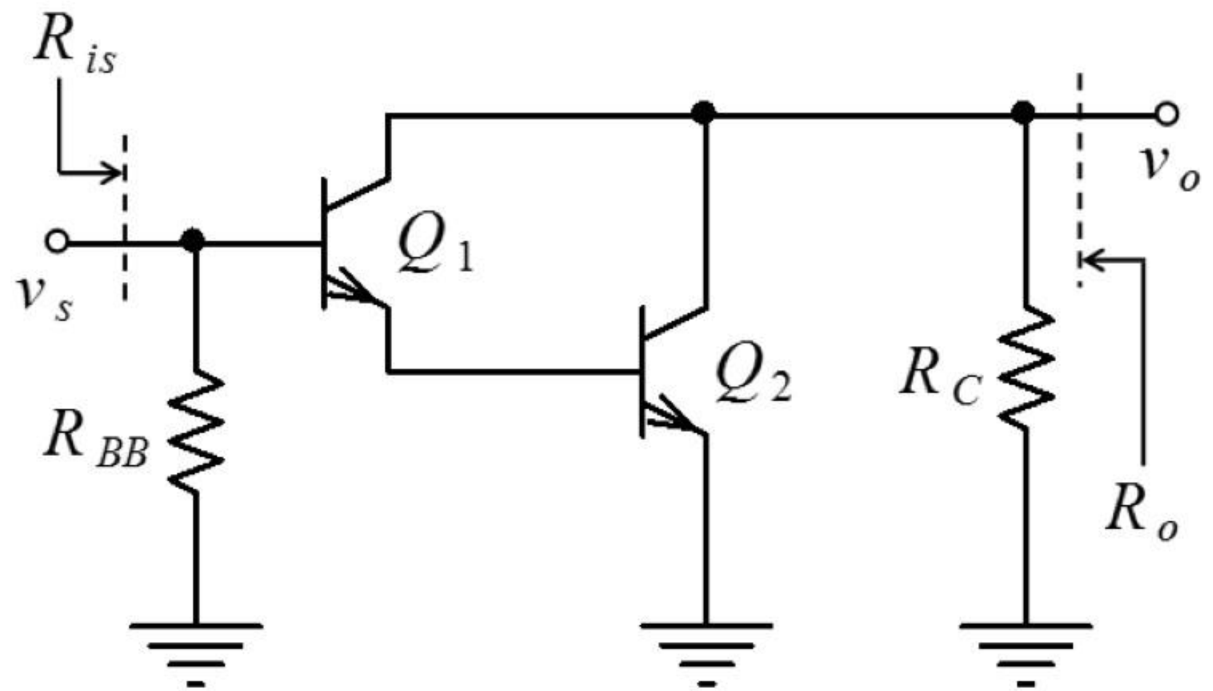
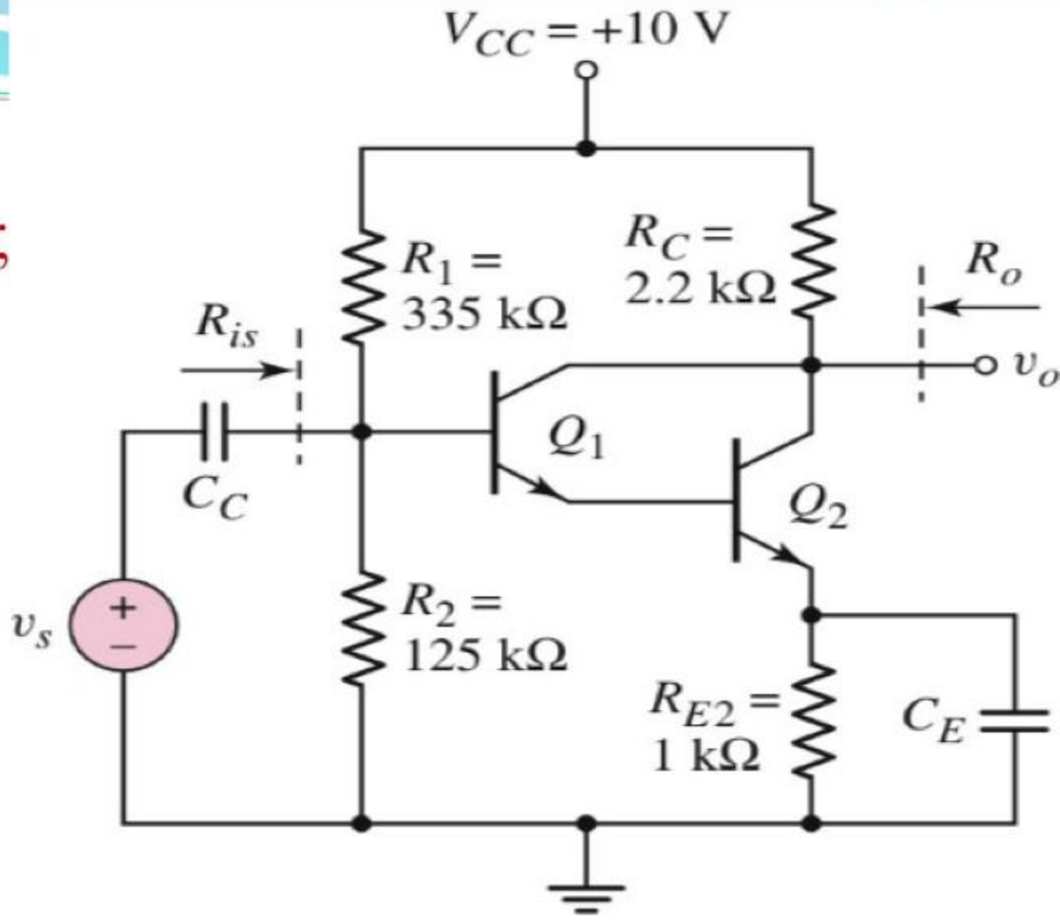
(b) The small-signal voltage gain (mid-band);

AC analysis





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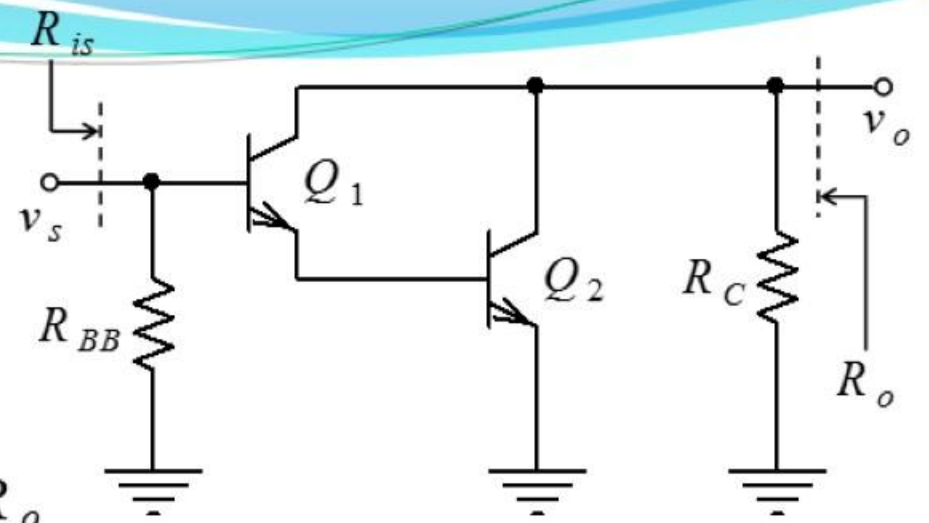
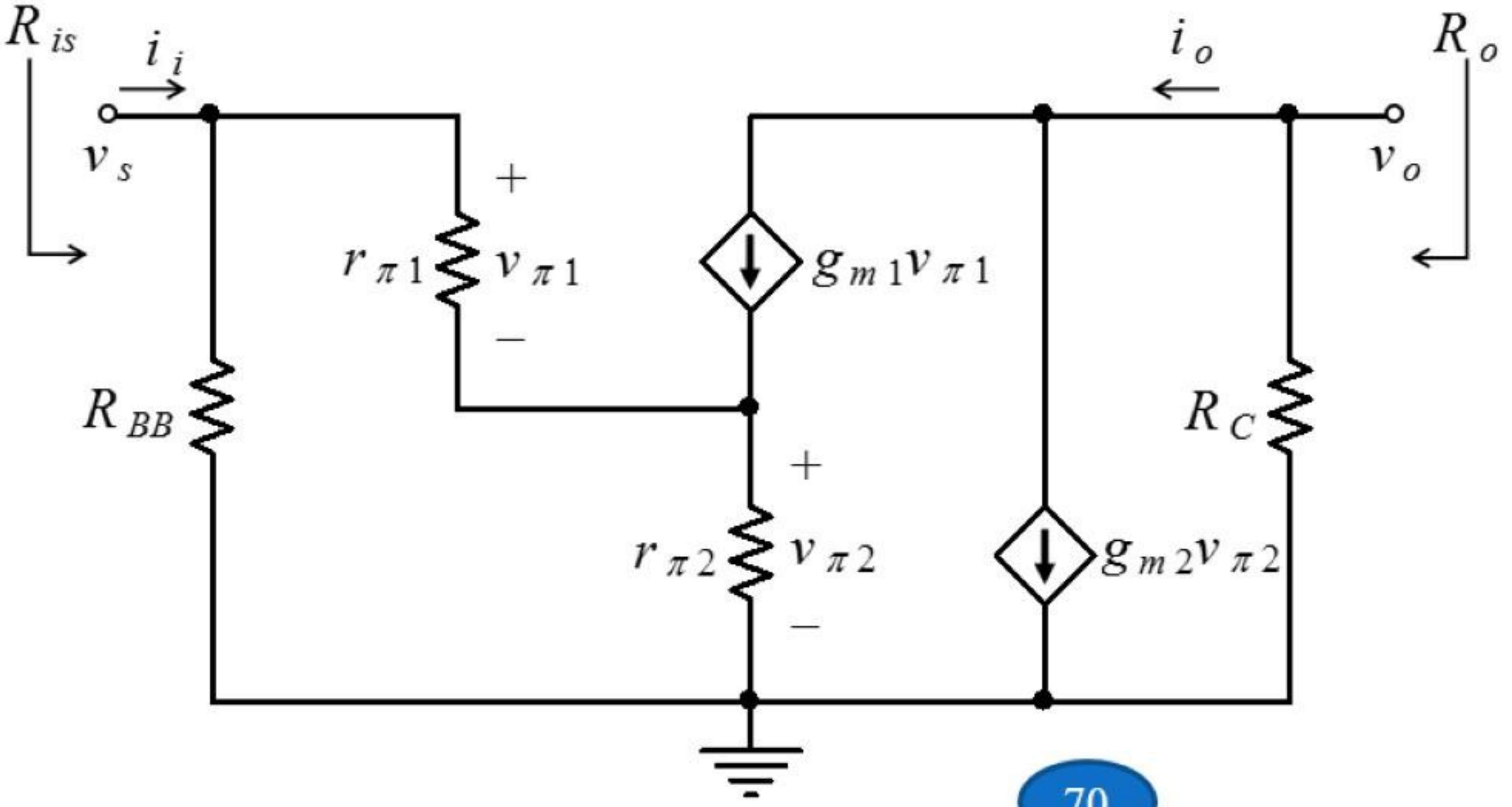
Using the hybrid-π model of transistor, the equivalent circuit becomes;





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$$g_{m1} = \frac{I_{CQ1}}{V_T} = \frac{12.8\ \mu\text{A}}{26\ \text{mV}} = 0.492\ \text{mA/V}$$

$$g_{m2} = \frac{I_{CQ2}}{V_T} = \frac{1.293\ \text{mA}}{26\ \text{mV}} = 49.73\ \text{mA/V}$$

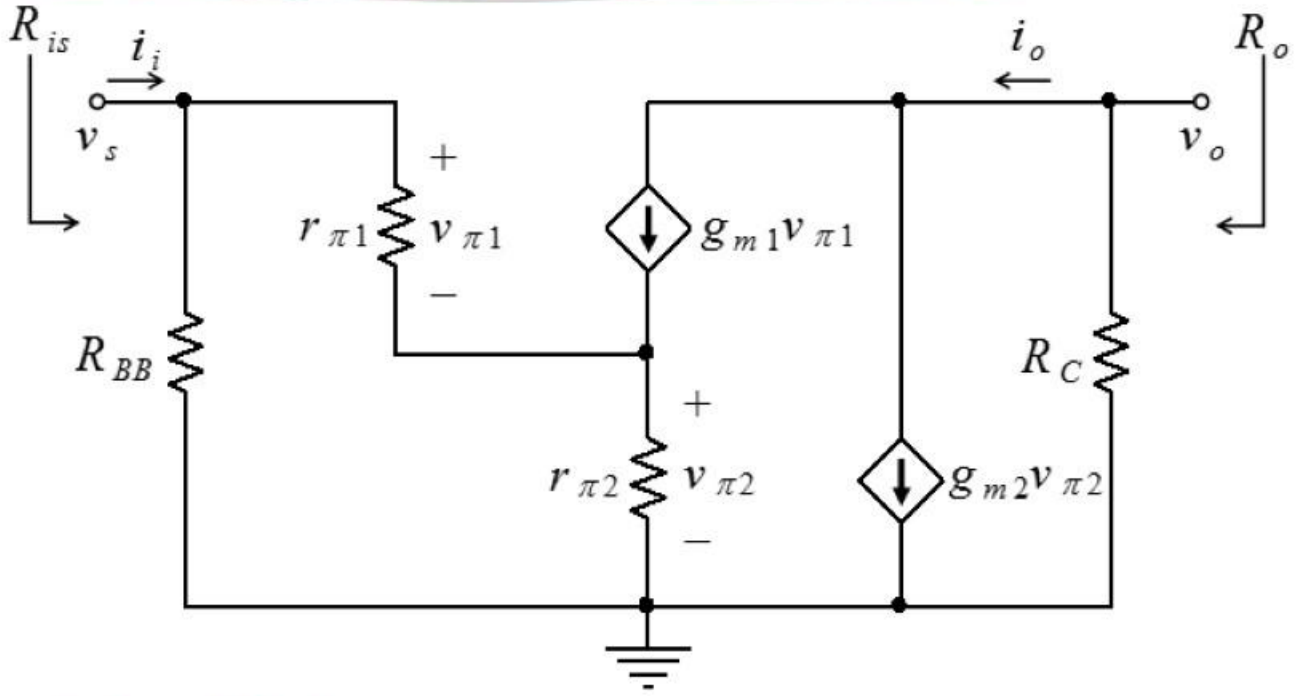
$$r_{\pi 1} = \frac{\beta_1}{g_{m1}} = \frac{100}{0.492 \times 10^{-3}} = 203.25\ \text{k}\Omega$$

$$r_{\pi 2} = \frac{\beta_2}{g_{m2}} = \frac{100}{49.73 \times 10^{-3}} = 2\ \text{k}\Omega$$

$$v_o = -\left(g_{m1}V_{\pi 1} + g_{m2}V_{\pi 2}\right)R_C$$

$$V_{\pi 2} = \left(\frac{V_{\pi 1}}{r_{\pi 1}} + g_{m1}V_{\pi 1}\right)r_{\pi 2} = \left(\frac{r_{\pi 2}}{r_{\pi 1}} + g_{m1}r_{\pi 2}\right)V_{\pi 1}$$

$$V_{\pi 2} = \left(1+\beta_1\right)\frac{r_{\pi 2}}{r_{\pi 1}}V_{\pi 1}$$



Substituting for $V_{\pi 2}$ in the expression for v_o and simplifying;

$$v_o = -\left[\frac{\beta_1 + \left(1+\beta_1\right)\beta_2}{r_{\pi 1}}\right]R_C V_{\pi 1}$$

$$v_s = V_{\pi 1} + V_{\pi 2}$$

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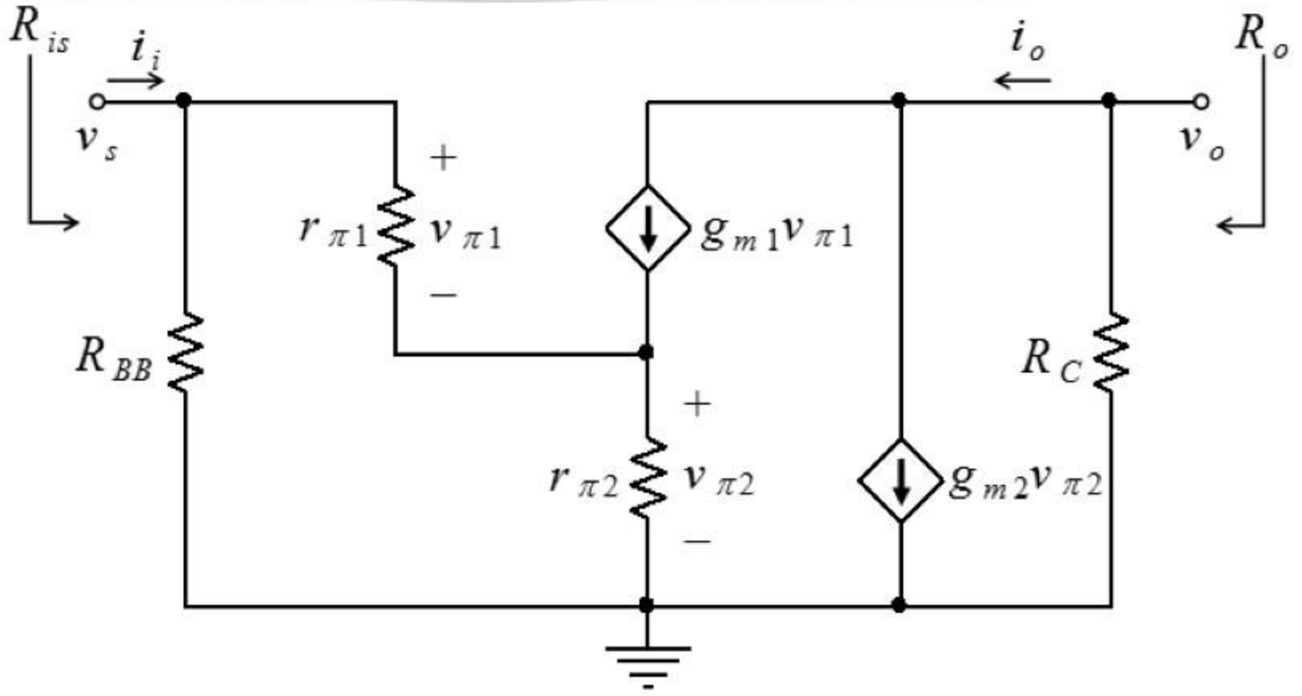
Substituting for $V_{\pi 2}$;

$$v_s = V_{\pi 1} + (1+\beta_1)\frac{r_{\pi 2}}{r_{\pi 1}} V_{\pi 1}$$

$$A_v = \frac{v_o}{v_s} = \frac{-\left[\dfrac{\beta_1 + (1+\beta_1)\beta_2}{r_{\pi 1}}\right] R_C V_{\pi 1}}{V_{\pi 1} + (1+\beta_1)\dfrac{r_{\pi 2}}{r_{\pi 1}} V_{\pi 1}}$$



Simplifying;

$$A_v = \frac{v_o}{v_s} = -\frac{[\beta_1 + (1+\beta_1)\beta_2] R_C}{r_{\pi 1} + (1+\beta_1) r_{\pi 2}}$$

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Substituting values;

$$A_v = -\frac{\left[100 + 100 + 100^2\right]2.2}{\left(203.25 + 2 + 100 \times 2\right)}$$

$$\boxed{A_v = -55.4 \text{ V/V}}$$

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$$R_{is} = R_{BB} \,//\, R_{ib}$$

$$R_{ib} = \frac{v_s}{i_b}$$

$$R_{ib} = \frac{v_s}{i_b} = r_{\pi 1} + (1+\beta_1) r_{\pi 2}$$

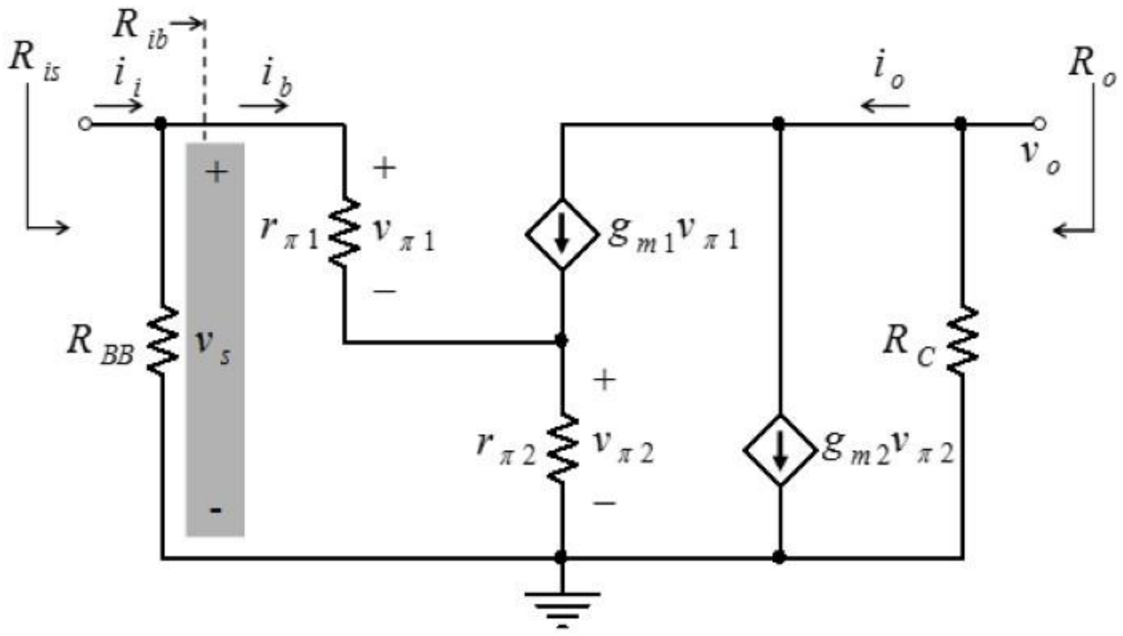
Substituting values;

$$R_{ib} = 203 + (1+100)2 = 405 \text{ k}\Omega$$

$$R_{is} = R_{BB} \,//\, R_{ib} = \frac{91 \times 405}{91 + 405}$$

$$\boxed{R_{is} = 73.6 \text{ k}\Omega}$$

$$\boxed{R_o = R_C = 2.2 \text{ k}\Omega}$$



$$\boxed{A_I = \frac{i_o}{i_i} = A_v \frac{R_{is}}{R_o} = -\ 1853}$$

E. Sawires

Thank You

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