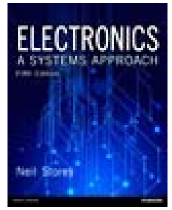
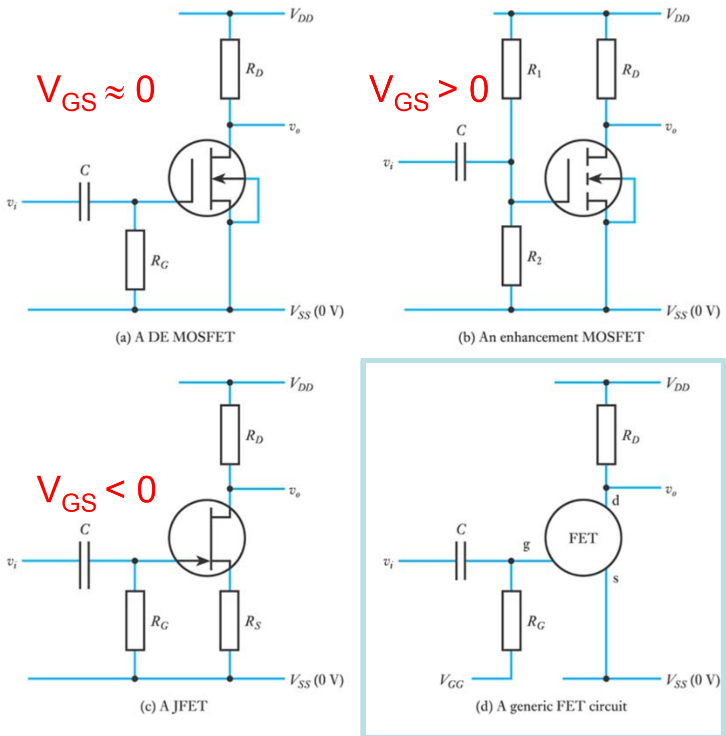
FET amplifiers-ac amplifier

Video 18A



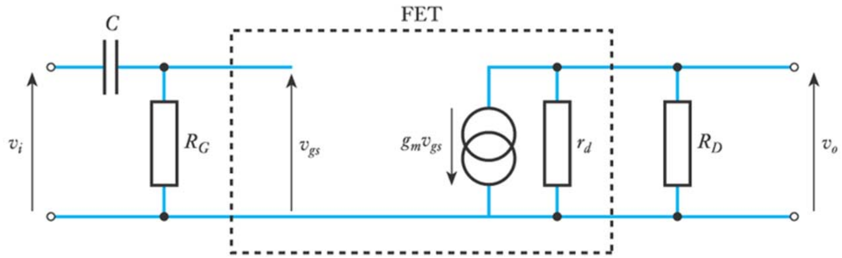
18.6



Equivalent

$\Rightarrow$

Circuit



$$\text{voltage gain} = \frac{v_o}{v_i} \approx -g_m R_D$$

$$r_i \approx R_G \quad \textit{can be made very big}$$

$$r_o \approx R_D \quad \textit{all for } r_d >> R_D$$

Where Transconductance

$g_m = dI_D/dV_{GS}$

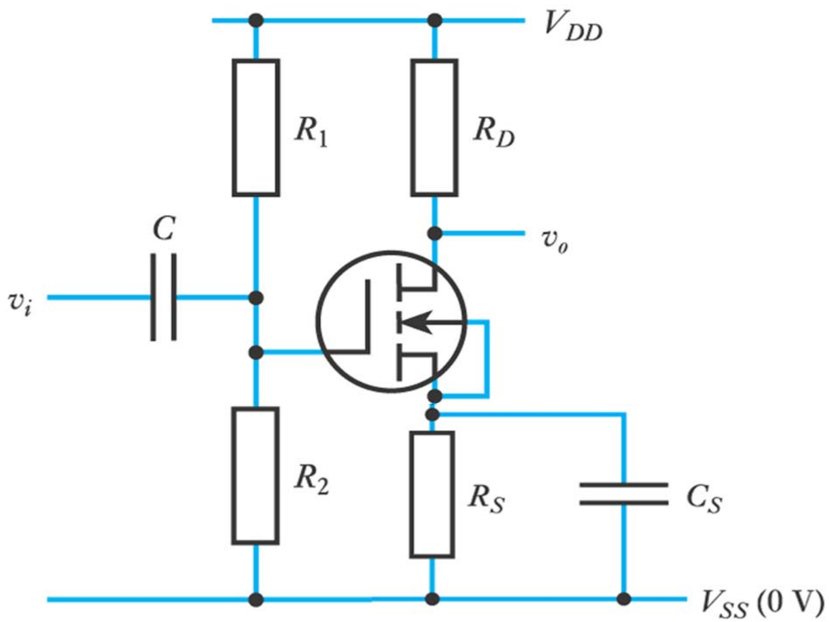
$= i_D/v_{GS}$

and the small letters refer to only the AC part (e.g. v_{DD}=0)

A negative feedback amplifier

Video 18C

- Feedback can be used not only to stabilise the biasing conditions of a circuit, but also its ***(low)*** voltage gain

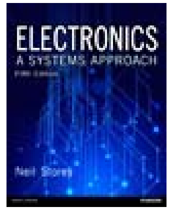


$$\text{voltage gain} = \frac{v_o}{v_i} \approx -\frac{R_D}{R_S}$$

$$r_i \approx R_1 // R_2$$

$$r_o \approx R_D$$

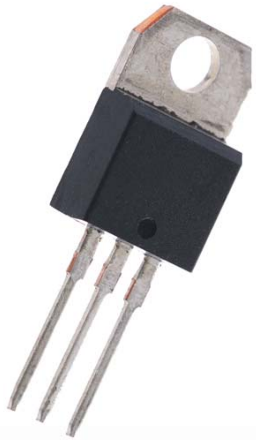
– characteristics set by ***stable passive components***

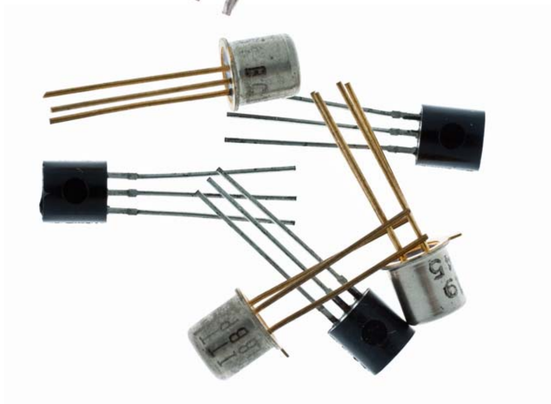


Chapter 19

Bipolar junction transistors

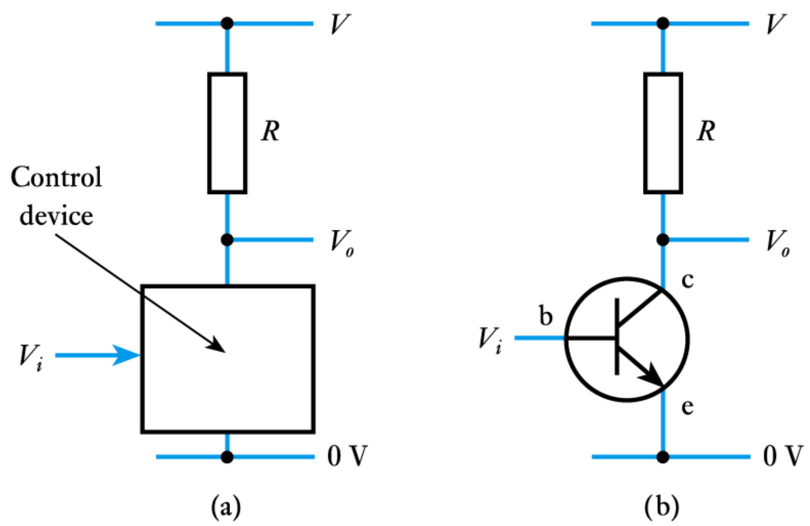
- Introduction
- An overview of bipolar transistors
- Bipolar transistor operation
- A simple amplifier
- Bipolar transistor characteristics
- Bipolar amplifier circuits
- Bipolar transistor applications
- Circuit examples



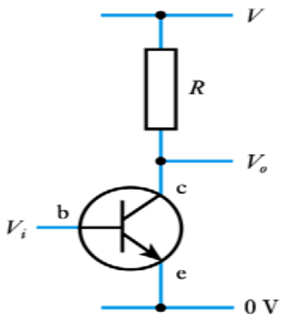


An overview of bipolar transistors

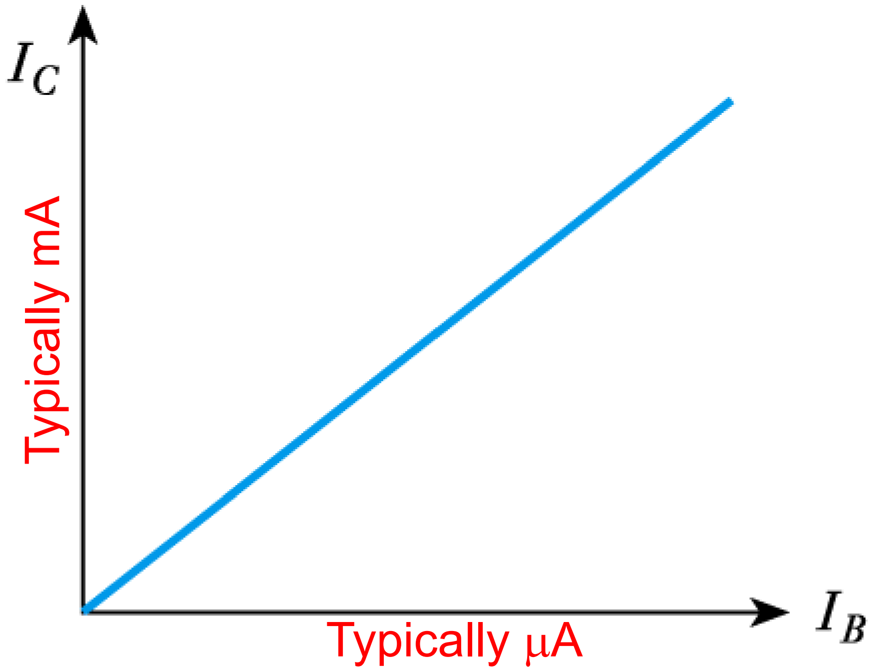
- FET is a single pn-junction
  - control is due to an electric *field or potential* at gate,
- Bipolar transistor has two pn-junctions
  - control is considered to be due to a *current* at the base
    - Current into one terminal determines the current between two others
    - As with a FET, a bipolar transistor can be used as a 'control device'



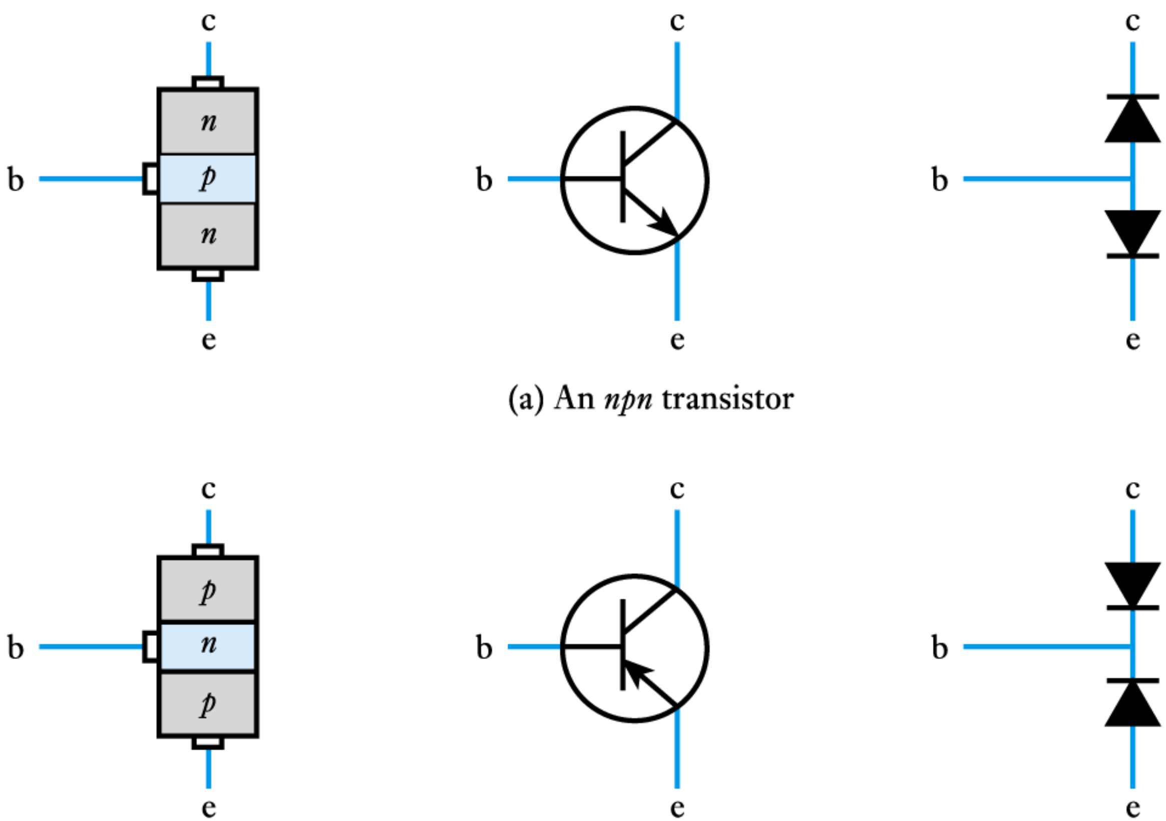
18.4



- Relationship between the collector current and the base current in a bipolar transistor
  - approximately linear
  - Collector current generally >> base current
  - the device provides **current gain**



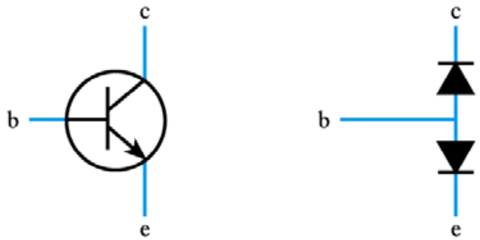
- **Construction**
  - two polarities: *npn* and *pnp*

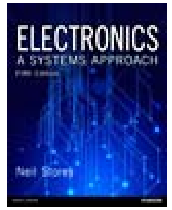


(a) An *npn* transistor

(b) An *pnp* transistor

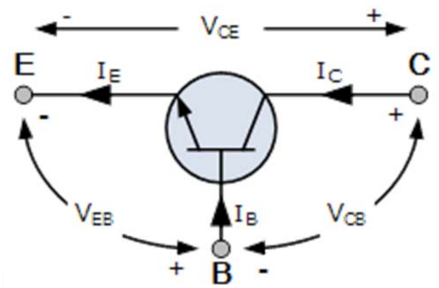
Bipolar transistor operation

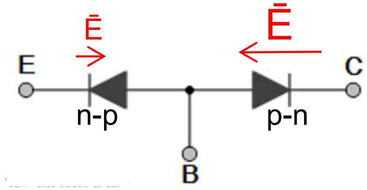




19.3

- We will consider *npn* transistors
  - *pnp* devices are similar but with different polarities of voltage and currents
  - when using *npn* transistors
    - collector is normally more positive than the emitter
    - V_{CE} might be a few volts
    - device resembles two back-to-back diodes – but has very different characteristics
    - with the base open-circuit negligible current flows from the collector to the emitter



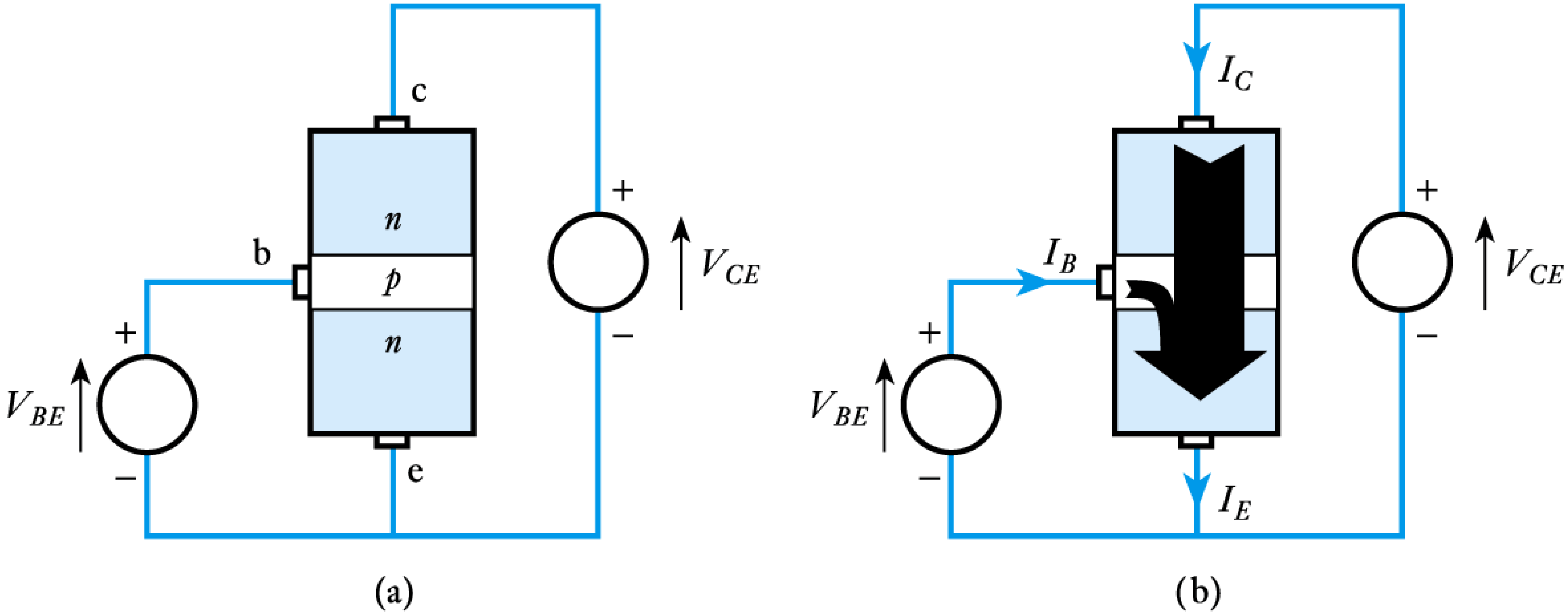


- If the base is made more positive than the emitter
  - This forward biases the base-emitter junction
  - The base region is lightly doped and very thin
  - Because it is lightly doped, the current produced is mainly electrons flowing from the emitter to the base
  - Because the base region is thin, most of the electrons entering the base get swept across the base-collector junction (by E field there) into the collector
  - This produces a collector current (I in opposite direction of electron motion) that is much larger than the base current – this gives **current amplification**

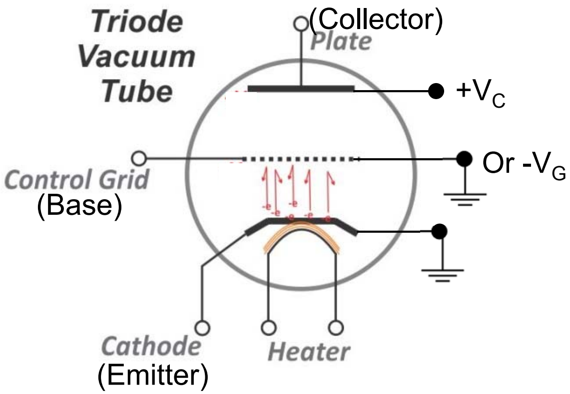
NPN ⇒ **N**ot **P**ointing i**N**

Negative-**P**ositive-**N**egative = on

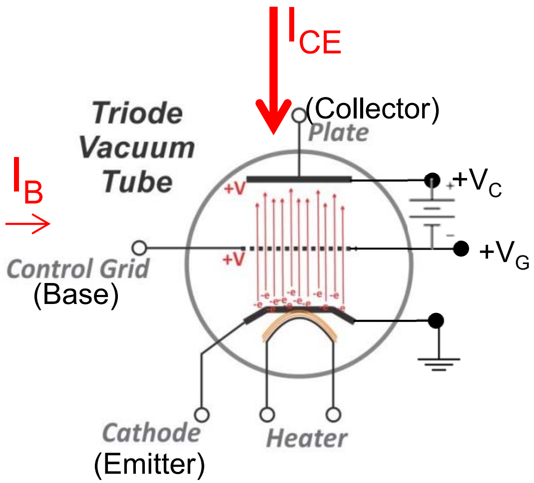
▪ Transistor action



Set the way-back machine, Sherman



- A NPN transistor!
- Off state,
  - Electrons emitted but shielded from $+V_C$ by grid that is at ground or slightly negative $-V_G$
  - Only a few make it to collector



- On state
  - Emitted electrons accelerate towards grid at $+V_G$
  - Most pass through the grid (a few electrons collected)
  - Remainder see $+V_C$ ($>V_G$), and accelerate towards it
  - Large number of electrons collected at collector.
  - Small Base current, large Collector→Emitter current

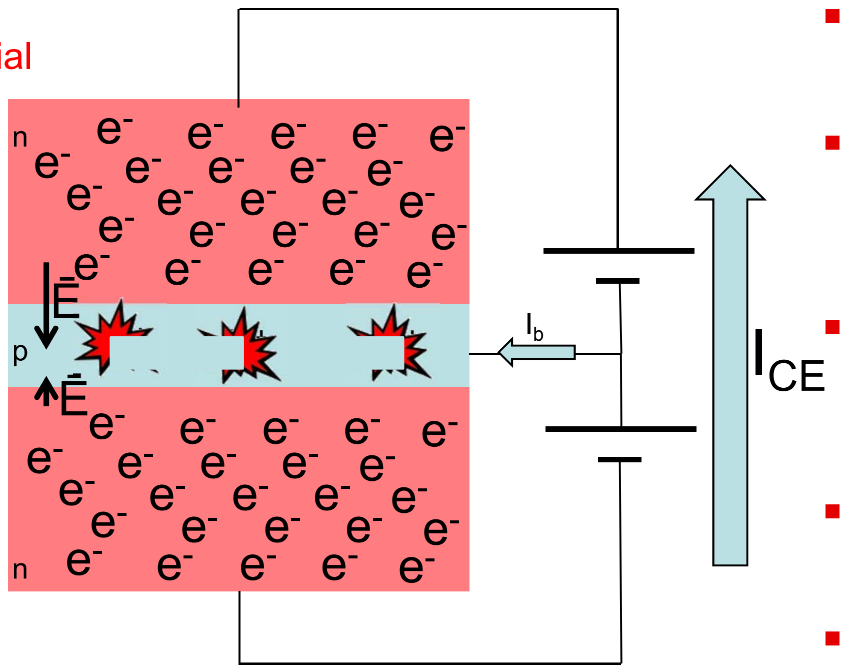
NPN transistor in “on” bias state

Current attracts electrons in collector material

Collector

Base

Emitter



Current repels electrons in emitter material

- Bias creates current flow from emitter to collector
- Electrons in collector recombine with holes from battery
- Electrons in emitter get repelled and pushed into base by electrons from battery
- Very few recombine in base. The few that do, create the small base current
- Most get pushed into the depletion region of the base-collector
- There they accelerate through the electric field into the collector
- Get large, continuous I_{CE} current

Is it a current or voltage device? Answer: Yes

- How do I increase I_B?
- Increase the forward bias ($I_B = I_{BS} \cdot e^{40 \cdot V_{BE}}$)
  - Where I_{BS} is a constant for the device
  - This lowers the base-emitter pn-barrier
  - This also makes the depletion region smaller
- More electrons are pushed through barrier
- I_C increases proportionately with I_B

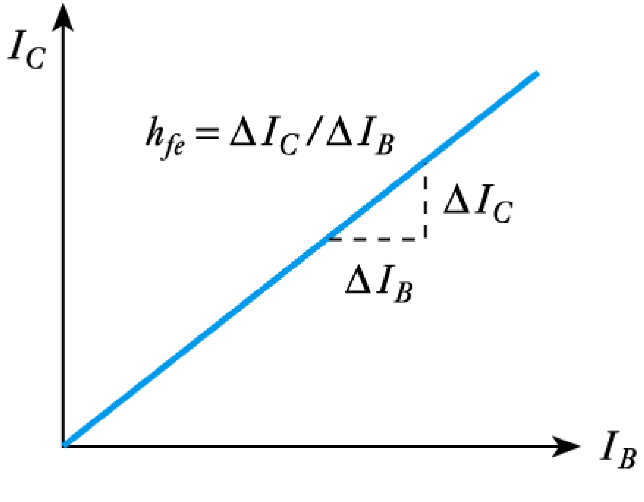
- Behaviour can be described by the **current gain, h_{fe}** or by the **transconductance, g_m** of the device

The AC gain of the device

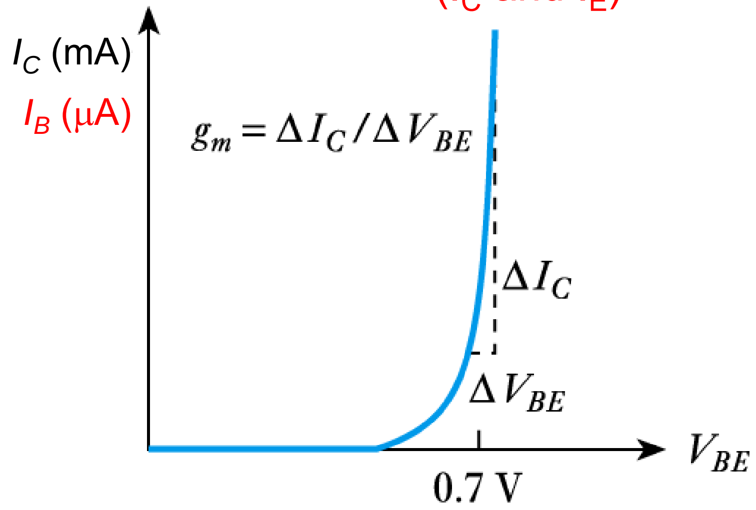
$i_c = h_{fe} \cdot i_b$ ($I \Rightarrow DC$, $i \Rightarrow AC$, or ΔI)

Looks like a diode since I_C is ≈ linear with I_B!

Note g_m depends on where device is operated (I_C and I_E)



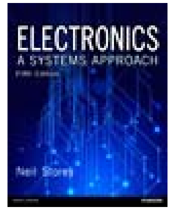
(a) Relationship between output current and input current



(b) Relationship between output current and input voltage

A simple amplifier ($\pm v_i$)

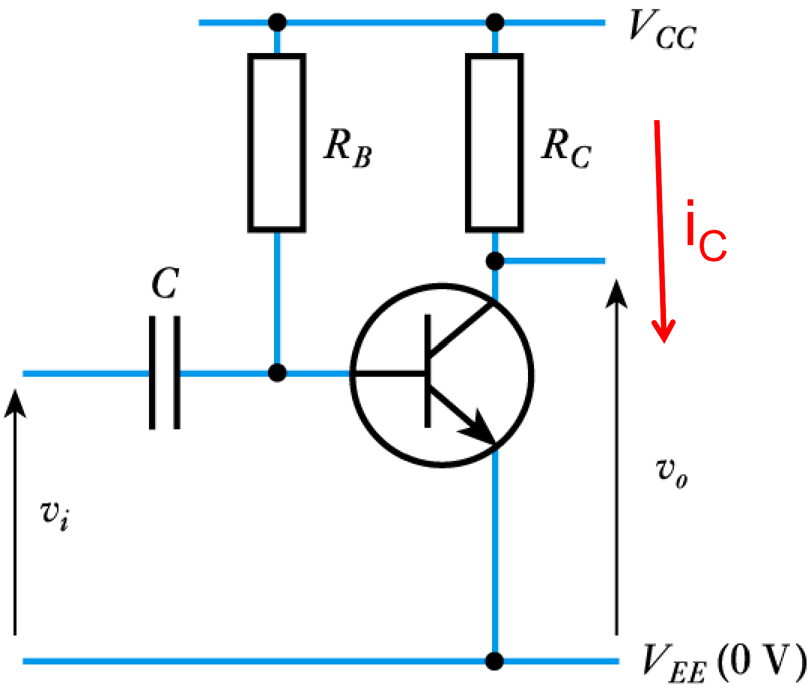
Video 19A



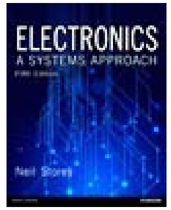
19.4

- The circuit shows a simple amplifier
  - R_B is used to ‘**bias**’ the transistor by injecting an appropriate base current
  - Forward biases B-E
  - C is a **coupling capacitor** and is used to couple the AC signal while preventing external circuits from affecting the bias
  - This is an **AC-coupled amplifier**

$V_o = V_{CC} - I_C \cdot R_C$ $\quad v_o = 0 - i_c \cdot R_c$



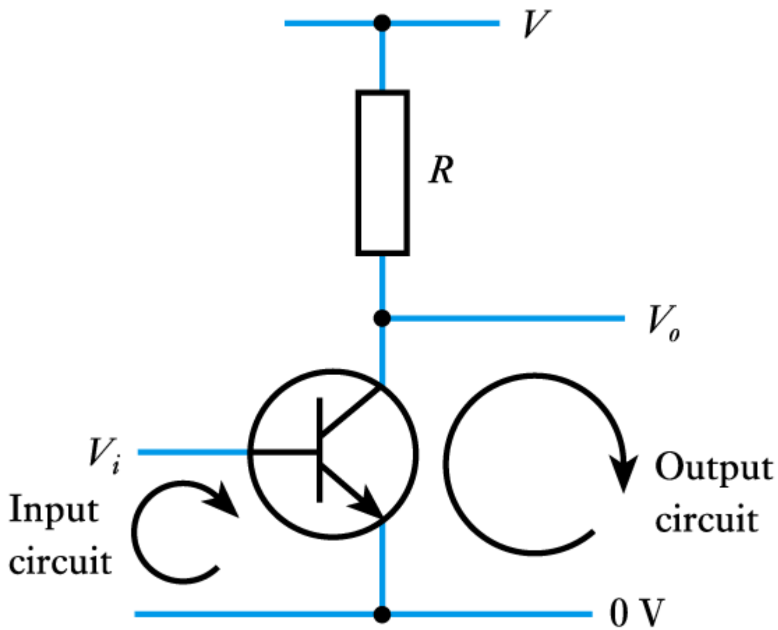
Base more +, increase i_C and more drop across $R_C \Rightarrow v_o$ decreases (inverting)



19.5

Bipolar transistor characteristics

- **Transistor configurations**
  - Transistors can be used in a number of configurations
  - Most common is as shown
  - *Emitter* terminal is common to input and output circuits
  - This is a **common-emitter** configuration
  - We will look at the characteristics of the device in this configuration

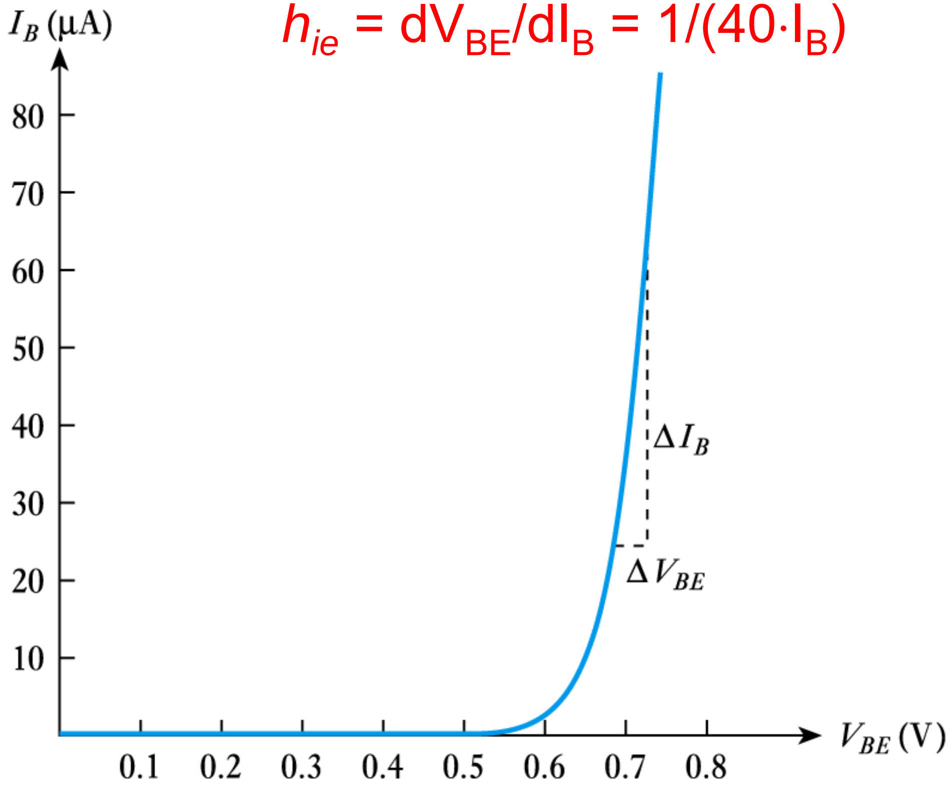


- **Input characteristics**
  - The input takes the form of a forward-biased *pn* junction
  - The input characteristics are therefore similar to those of a semiconductor diode

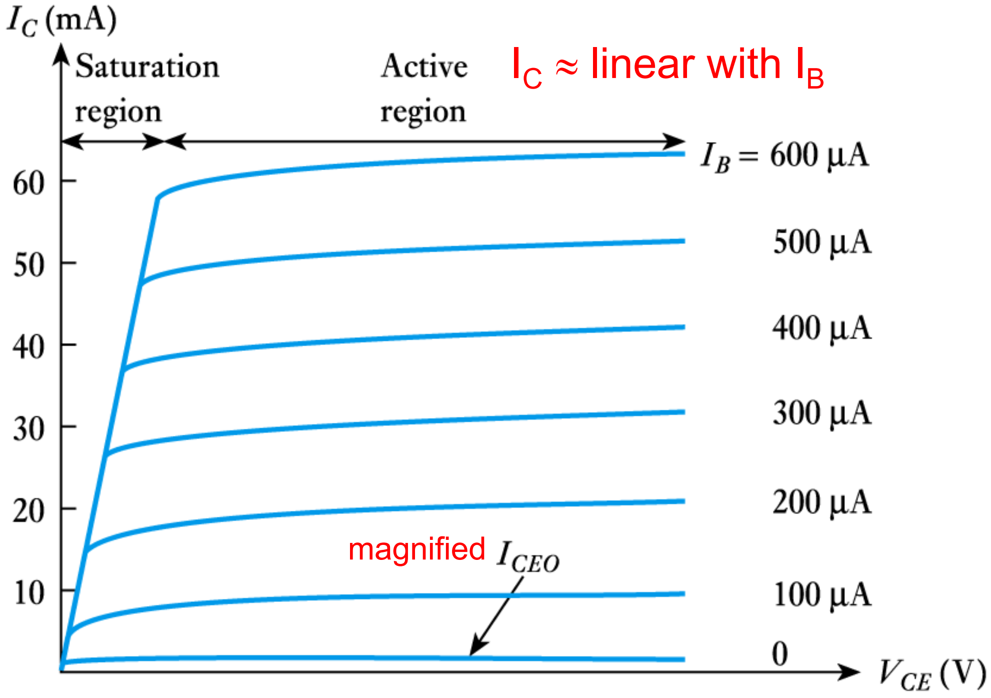
$I_B \approx Constant \cdot e^{40V_{BE}}$

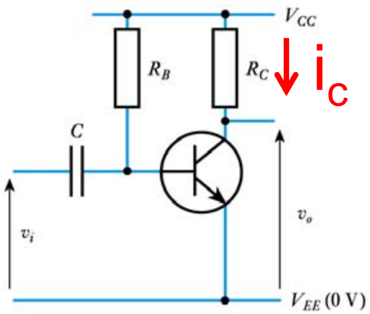
$\therefore$ input resistance:

$h_{ie} = dV_{BE}/dI_B = 1/(40 \cdot I_B)$



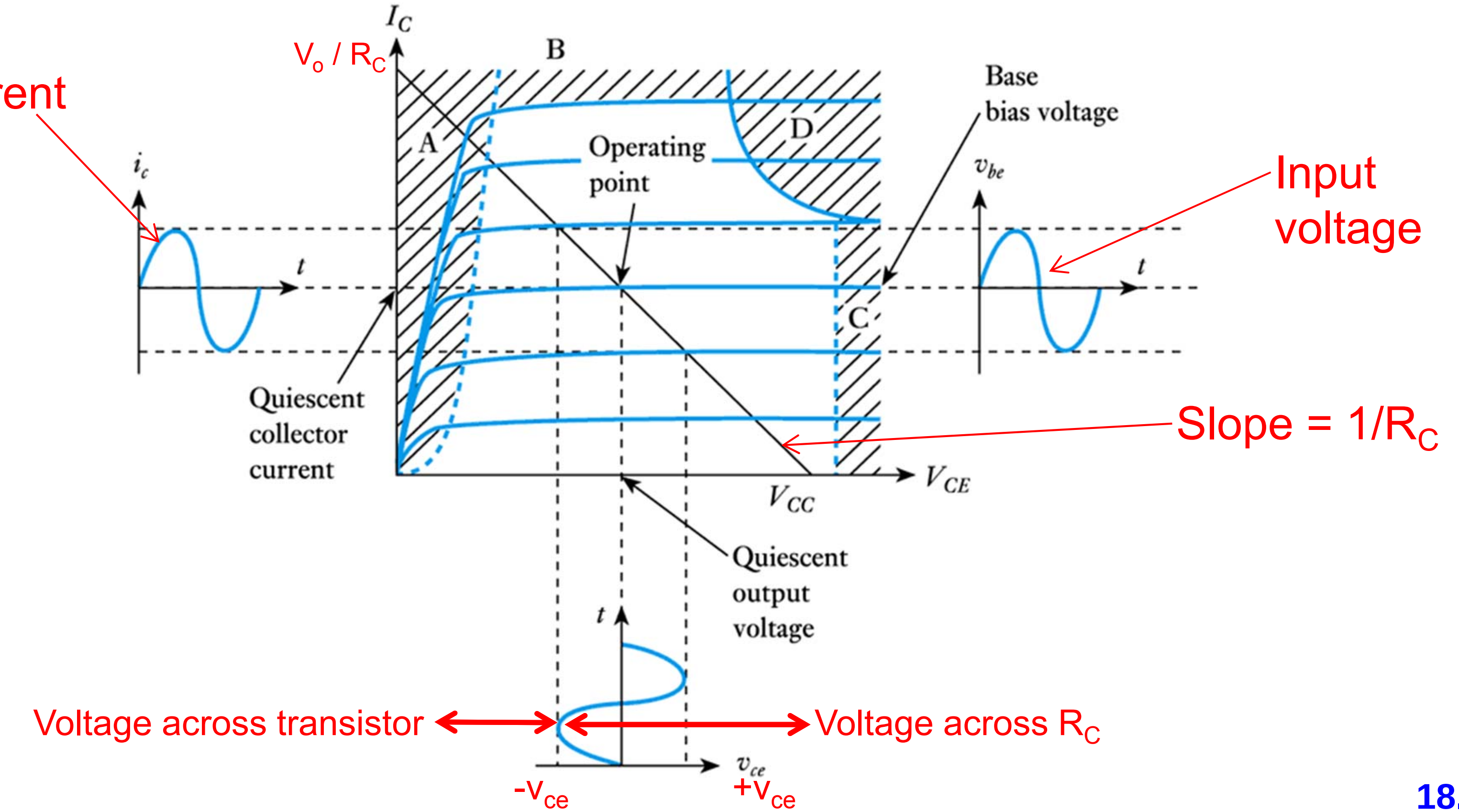
- **Output characteristics**
  - region near to the origin is the **saturation region**
  - this is normally avoided in linear circuits
  - slope of lines represents the **output resistance** (r_o)





$V_o = V_{CC} - I_C \cdot R_C$ $\quad v_o = 0 - i_c \cdot R_c$

- Choice of operating point in a simple amplifier



- **Transfer characteristics**
  - can be described by either the current gain or by the transconductance
  - DC current gain h_{FE} or β is given by I_C / I_B
  - AC current gain h_{fe} is given by i_c / i_b
  - transconductance g_m $(=dI_C/dV_{BE})$ is given approximately by

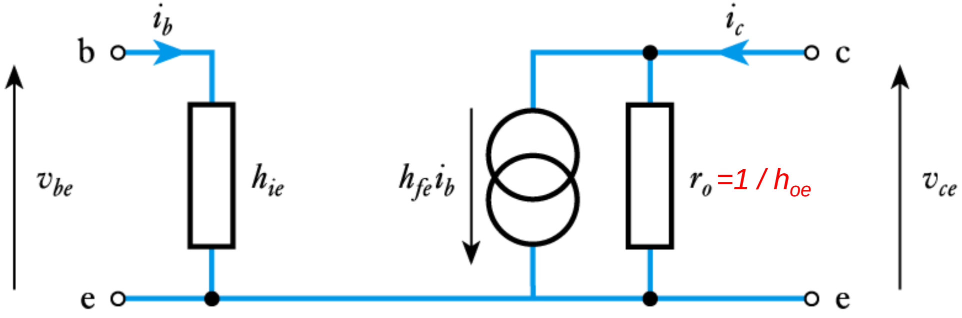
$$g_m \approx 40 \cdot I_C \approx 40 \cdot I_E \text{ siemens}$$

$$(Since\ I_C \approx Constant \cdot e^{40V_{BE}})$$

- the units of g_m are those of admittance
- therefore $1/g_m$ has the units of resistance
- the quantity $1/g_m$ is termed the **emitter resistance r_e**
- therefore $$r_e = \frac{1}{g_m} \approx \frac{1}{40I_C} \approx \frac{1}{40I_E}\,\Omega$$

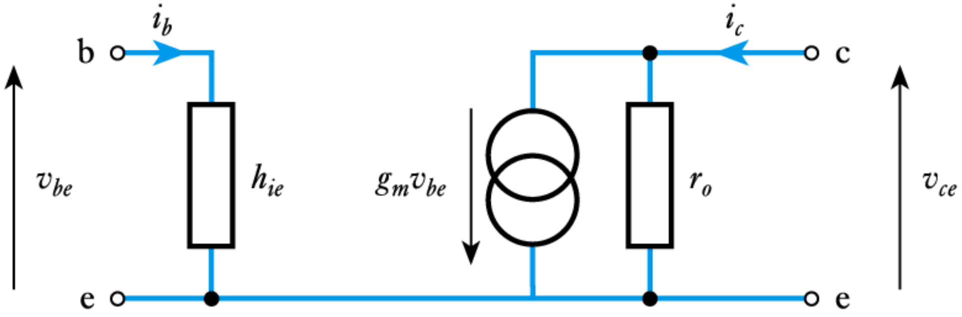
▪ Simple equivalent circuits for a bipolar transistor

Base current control



(a)

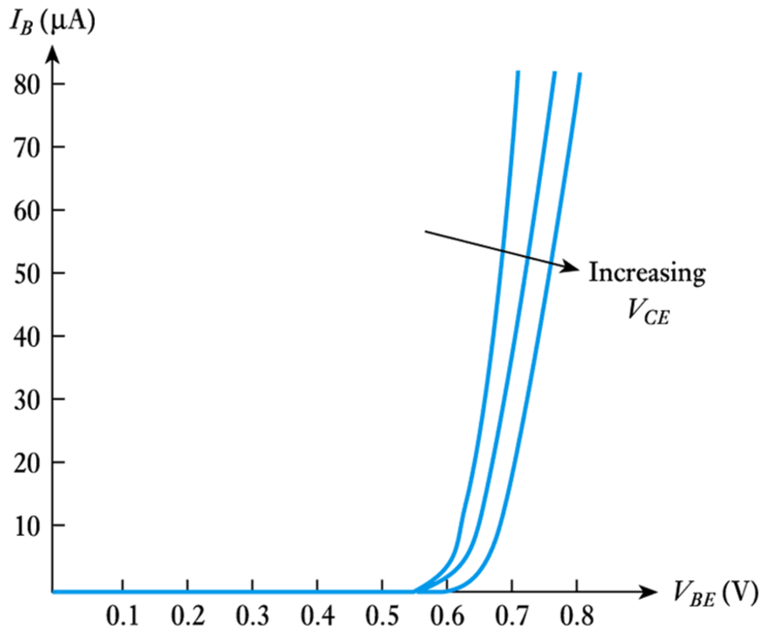
Base voltage producing a base current control



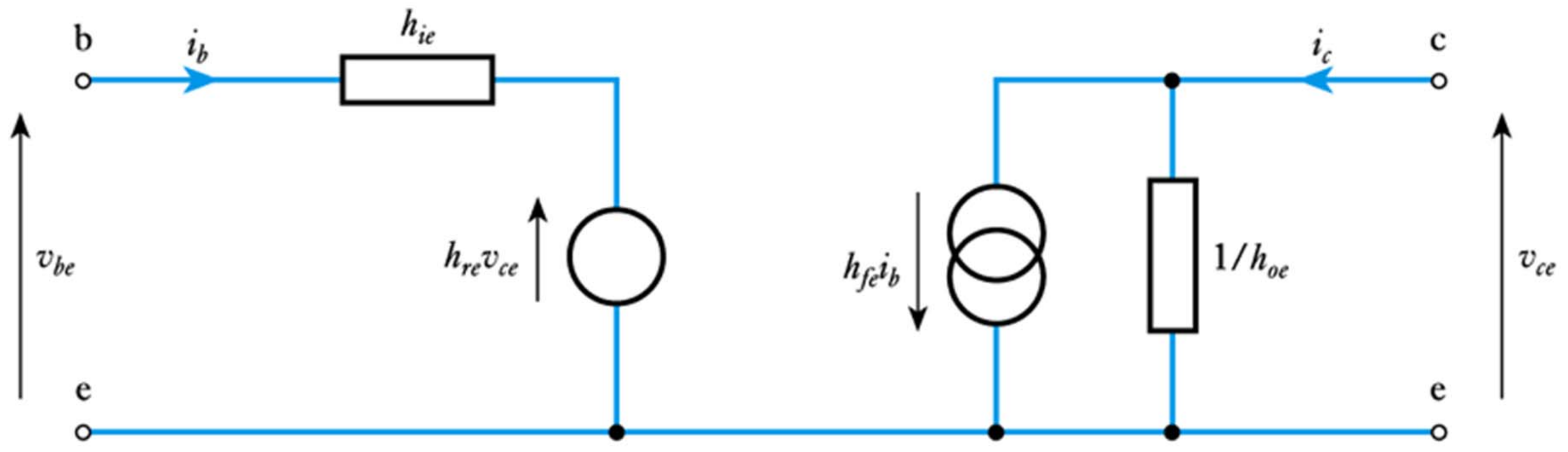
(b)

V_{CE} affects the base bias
Called the Early effect

- **Limitations of the simple models**
  - While the simple models shown above give a reasonable representation of the behaviour of devices they do not show the effects of the output voltage on the input (as shown here)
  - This can be modelled by the reverse transfer ratio h_{re}

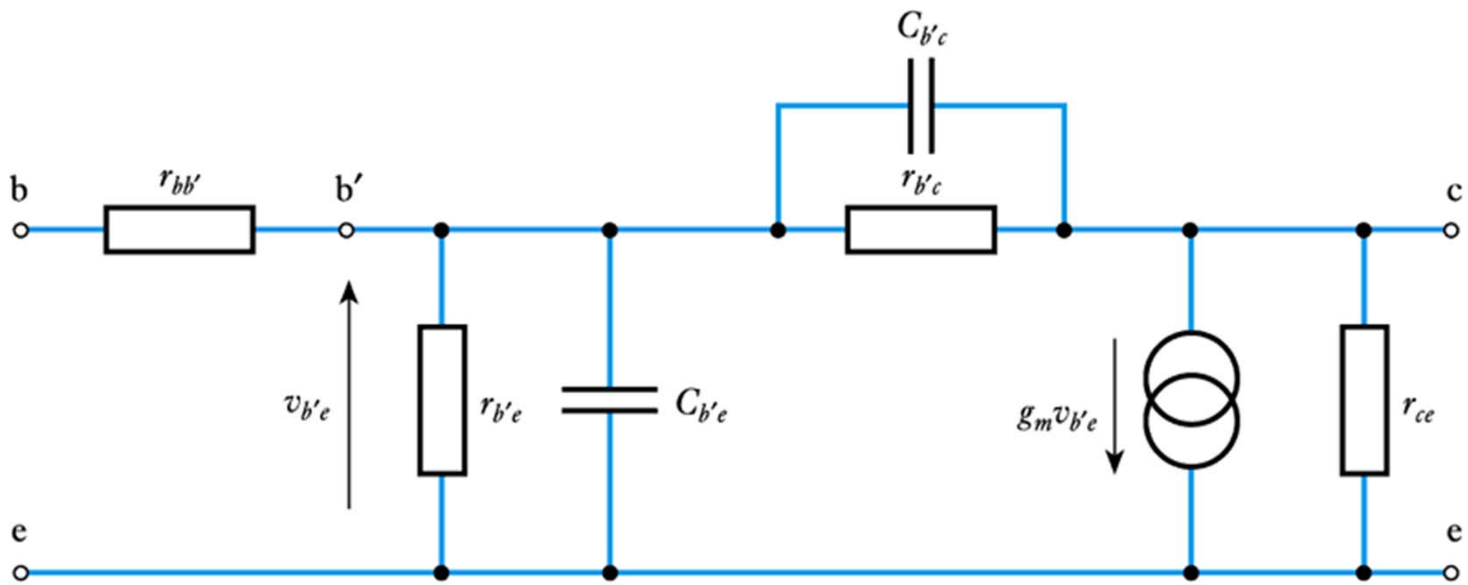


- **The hybrid-parameter model**
  (accounting for Early effect)

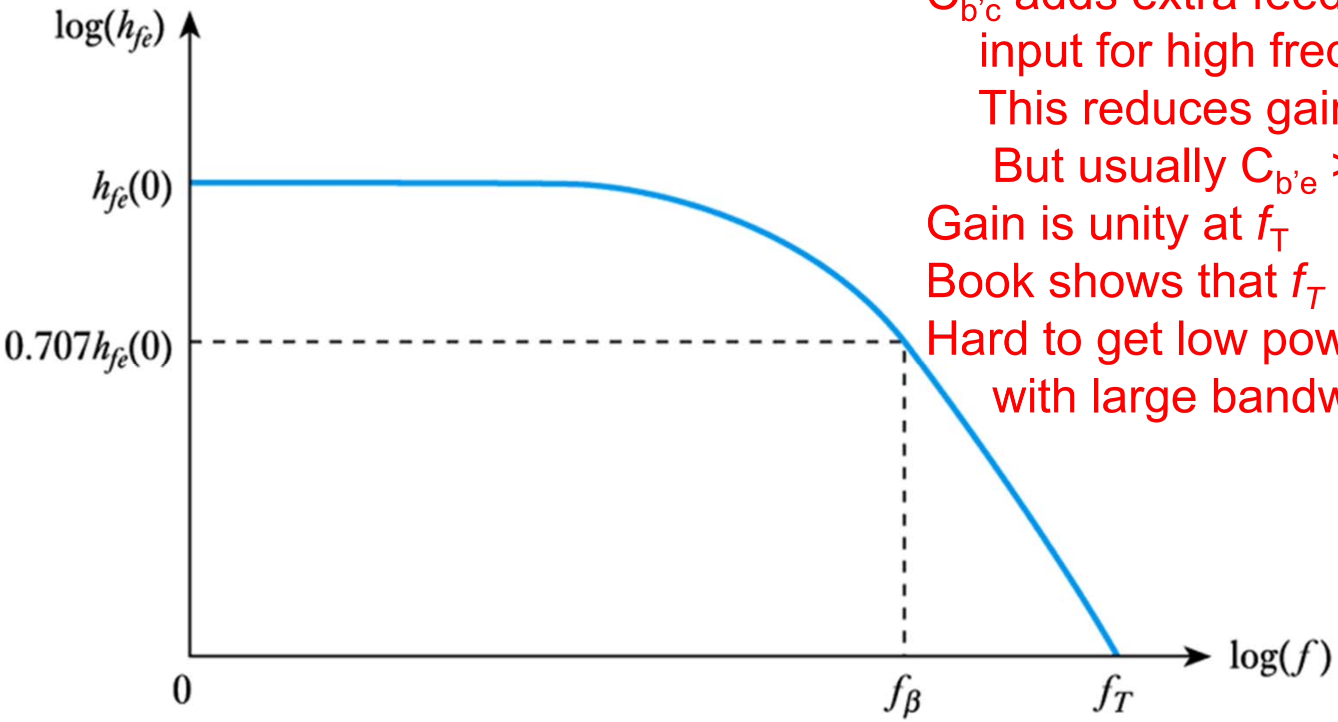


The hybrid-π model

- gives a better representation at high frequencies
- High $f \Rightarrow$ base, emitter and collector coupled capacitively



Bipolar transistors at high frequencies



$C_{b'e}$ creates fall at high frequencies
$C_{b'c}$ adds extra feedback voltage at input for high frequencies,
This reduces gain even more.
But usually $C_{b'e} >> C_{b'c}$
Gain is unity at f_T
Book shows that f_T and f_β are $\propto I_E$
Hard to get low power consumption with with large bandwidths!

BJT parameters for common emitter configuration (subscript $_e$)

- **Input$_i$ Output$_o$ Forward$_f$ Reverse$_r$**

h_{FE}	DC gain	I_C / I_B	
h_{fe}	AC gain	i_c / i_b	$h_{FE} \approx h_{fe}$ (mostly)
g_m	Transconductance	$\Delta I_C / \Delta V_{BE} = i_c / v_{be}$	$\sim 40 \cdot I_C \approx 40 \cdot I_E$
h_{ie}	Small signal input resistance	$\Delta V_{BE} / \Delta I_B = v_{be} / i_b$	$\sim 1 / (40 \cdot I_B)\ \Omega \approx h_{fe} / (40 \cdot I_C)$
h_{oe}	Output admittance ($1/r_o$) where r_o = Slope in the active region	$\Delta I_C / \Delta V_{CE} = i_c / v_{ce}$	
r_e	Emitter resistance	$\Delta V_{BE} / \Delta I_C = v_{be} / i_c = 1/g_m$	$\approx v_{be} / i_e$ that is, $h_{ie} = h_{fe} \cdot r_e$
h_{re}	Early effect (V_{CE} affects bias V_{BE})	$\Delta V_{CE} / \Delta V_{BE}$	

$$h_{FE} = \frac{I_C}{I_B}$$

$$I_E = I_C + I_B = (h_{FE} + 1) \cdot I_B$$

$$\text{but because } h_{FE} >> 1,$$

$$\boxed{I_E \approx h_{FE} \cdot I_B = I_C}$$

$$I_B = I_{BS} \cdot e^{40 \cdot V_{BE}} \quad \text{where } I_{BS} \text{ is constant}$$

$$I_C = h_{FE} \cdot I_B = h_{FE} \cdot I_{BS} \cdot e^{40 \cdot V_{BE}}$$

$$g_m = \frac{\Delta I_C}{\Delta V_{BE}} = \frac{dI_C}{dV_{BE}} = 40 \cdot h_{FE} \cdot I_{BS} \cdot e^{40 \cdot V_{BE}}$$

$$g_m = \qquad = 40 \cdot I_C \approx 40 \cdot I_E$$

BJT parameters for common emitter configuration (subscript $_e$)

- Inp … erse$_r$

h_{FE}	D	
h_{fe}	A	ly)
g_m	T	
h_{ie}	S	$\approx h_{fe} / (40 \cdot I_C)$
h_{oe}	O w	
r_e	E	is, $h_{ie}=h_{fe} \cdot r_e$
h_{re}	E	

$h_{FE} = \frac{I}{I}$ … constant

$I_E = I_C$ …

$but\ b$ … $_{BS} \cdot e^{40 \cdot V_{BE}}$

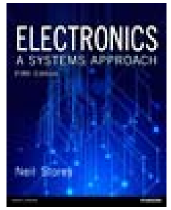
$I_E \approx h$ … $0 \cdot I_E$

We will only use these to derive results

Just Remember the results!

Key points

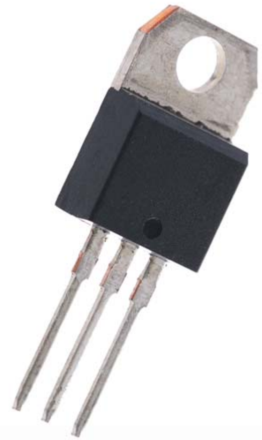
- Bipolar transistors are widely used in both analogue and digital circuits
- They can be considered as either voltage-controlled or current-controlled devices
- Their characteristics may be described by their current gain or by their transconductance
- Many amplifier circuits use transistors in a common-emitter configuration where the input is applied to the base and the output is taken from the collector

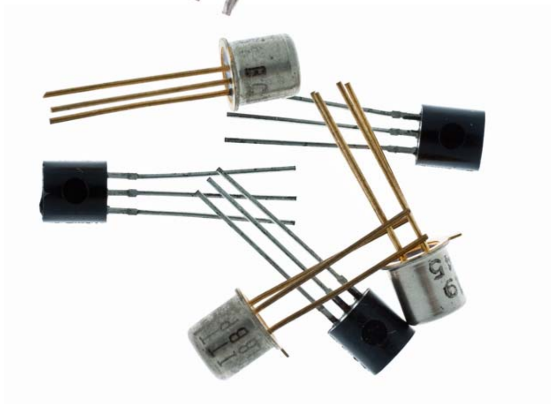


Next time: Bipolar junction transistors

Chapter 19

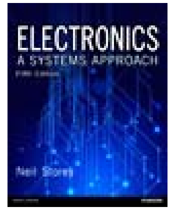
- Introduction
- An overview of bipolar transistors
- Bipolar transistor operation
- A simple amplifier
- Bipolar transistor characteristics
- Bipolar amplifier circuits





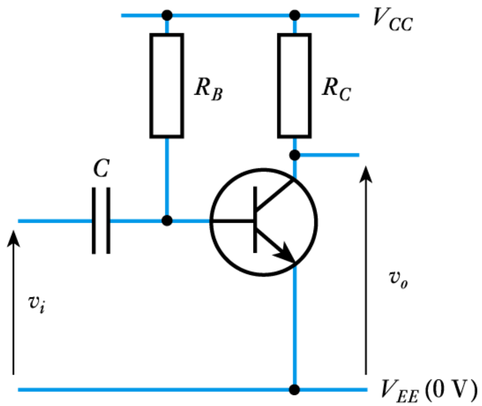
Bipolar amplifier circuits

Video 19A



19.6

- **Analysis of a simple amplifier**
  - Earlier we looked at a simple amplifier
  - This is an AC-coupled amplifier
  - It is convenient to look at its **DC (or quiescent)** behaviour separately from its **AC (or small signal)** behaviour

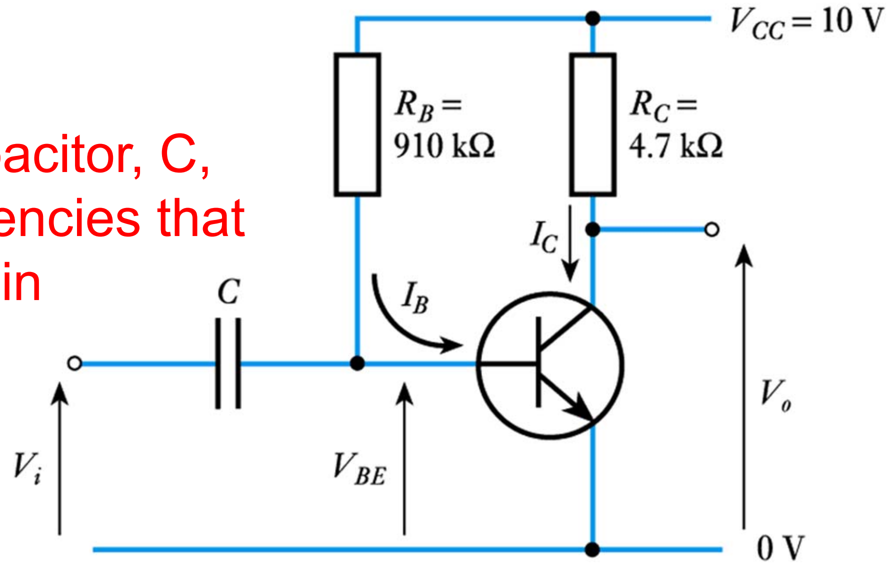


DC analysis of a simple amplifier

- **Example** – see **Example 19.1** from course text

  Determine the quiescent collector current and the quiescent output voltage of the following circuit, given that the h_{FE} of the transistor is 100

Note AC coupling capacitor, C, will remove low frequencies that we are not interested in



- **Example (continued)**
  - The base-to-emitter voltage V_{BE} is approximately 0.7 V.
  - Therefore

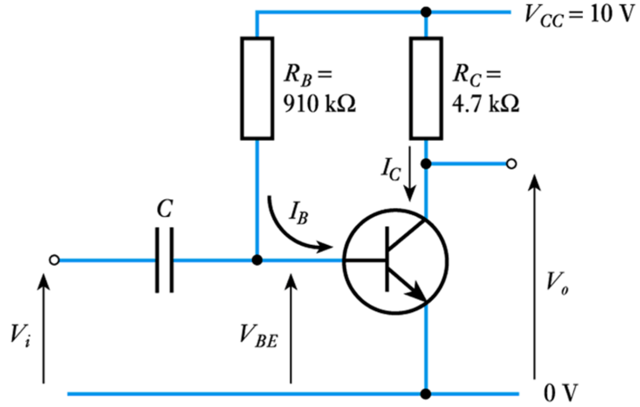
$$I_B = \frac{V_{CC} - V_{BE}}{R_B} = \frac{10 - 0.7\ \text{V}}{910\ \text{k}\Omega} = 10.2\ \mu\text{A}$$

  - Therefore

$$I_C = h_{FE} I_B = 100 \times 10.2\ \mu\text{A} = 1.02\ \text{mA}$$

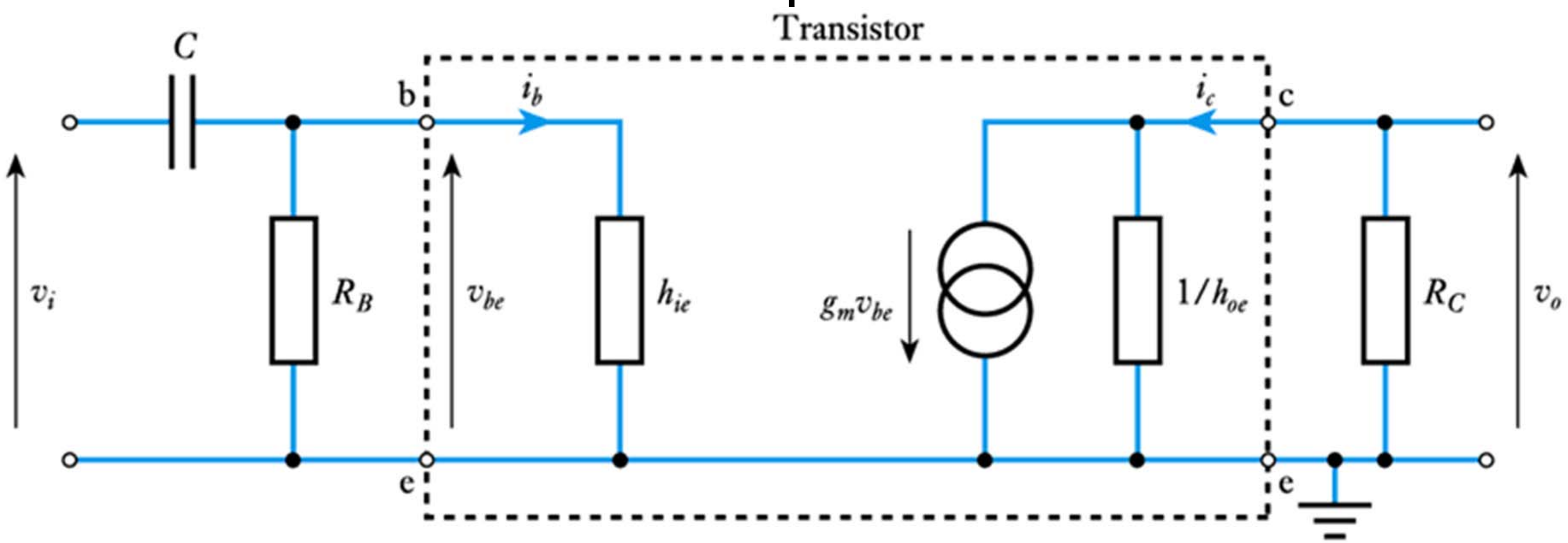
  - and

$$V_o = V_{CC} - I_C R_C = 10 - 1.02 \times 10^{-3} \times 4.7 \times 10^{3} \approx 5.2\ \text{V}$$

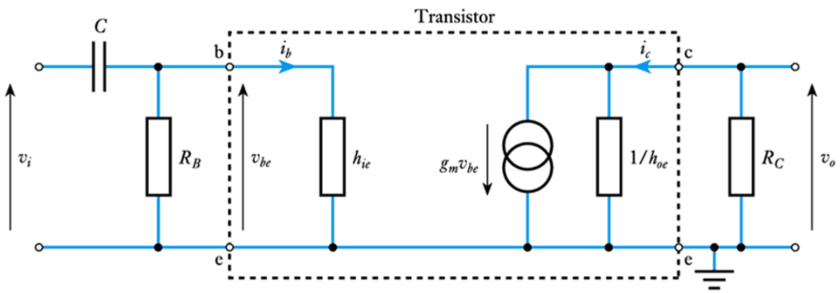


Small signal analysis of an amplifier

- To determine the small-signal behaviour of the circuit, we first construct a small-signal equivalent circuit
  - We start with our model of the transistor
  - Then add the other components



- From the equivalent circuit,



$$v_{be} = v_i$$

and therefore

$$v_o = -g_m v_{be}\left(\frac{1}{h_{oe}} // R_C\right) = -g_m v_i\left(\frac{1}{h_{oe}} // R_C\right)$$

so

$$\text{voltage gain} = \frac{v_o}{v_i} = -g_m\left(\frac{1}{h_{oe}} // R_C\right) = -g_m \frac{R_C}{h_{oe}R_C + 1}$$

Usually, $1/h_{oe} >> R_C$, so

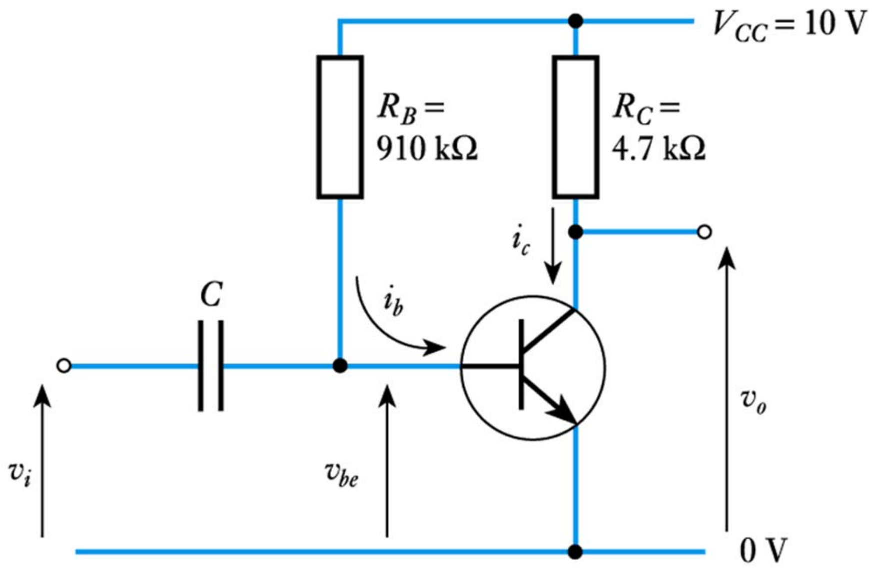
$$\text{voltage gain} = \frac{v_o}{v_i} = -g_m R_C = -\frac{R_C}{r_e}$$

$$\text{voltage gain} = \frac{v_o}{v_i} = -g_m R_C = -\frac{R_C}{r_e}$$

Had h_{FE} = 100 and h_{oe} = 100 μS, calculated $I_E \approx I_C$ = 1.02 mA, I_B=10.2μA
So we need to get g_m for the gain, and h_{ie}, for the input resistance

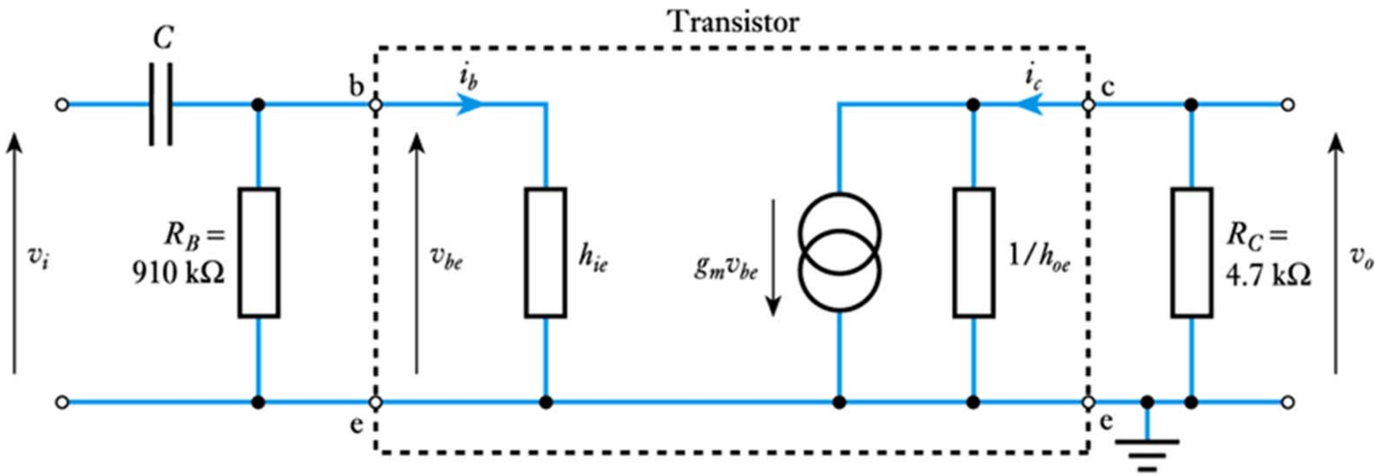
- **Same Example** – see **Example 19.2** from course text

  Determine the small signal voltage gain, input resistance and output resistance of the following circuit, given that h_{fe} = 100 and h_{oe} = 100 μS



Example (continued)

The small signal equivalent circuit and we want g_m and h_{ie}



Definitions:

$$g_m = \frac{i_c}{v_{be}} \Rightarrow i_c = g_m \cdot v_{be}$$

$$h_{fe} = \frac{i_c}{i_b} \Rightarrow i_c = h_{fe} \cdot i_b$$

$$\text{then } i_b \cdot h_{fe} = g_m \cdot v_{be}$$

$$h_{ie} = \frac{v_{be}}{i_b} \Rightarrow i_b = \frac{v_{be}}{h_{ie}}$$

$$\text{so } \frac{v_{be}}{h_{ie}} \cdot h_{fe} = g_m \cdot v_{be}$$

$$\text{or } h_{ie} = \frac{h_{fe}}{g_m}$$

Remember :

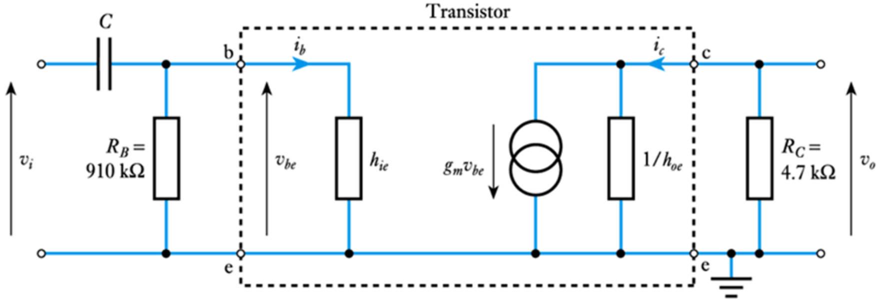
$$I_B = I_{BS} \cdot e^{40 \cdot V_{BE}}$$

$$g_m = \frac{i_c}{v_{be}} = \frac{\Delta I_C}{\Delta V_{BE}} = \frac{\partial (h_{FE} \cdot I_B)}{\partial V_{BE}} = 40 \cdot I_C$$

And :

$$h_{ie} = \frac{h_{fe}}{g_m}$$

- We first need to establish g_m and h_{ie}. From the earlier example $I_E \approx I_C$ = 1.02 mA Therefore



$$g_m = \frac{dI_c}{dv_{be}} \approx 40 \cdot I_C \approx 40 \cdot I_E \approx 40.8 \text{ mS}$$

$$h_{ie} \approx \frac{h_{fe}}{40 I_E} \approx \frac{100}{40 \times 1.02 \times 10^{-3}} \approx 2.45 \text{ k}\Omega$$

- **Voltage gain**

$$\text{voltage gain} = -g_m \frac{R_C}{h_{oe} R_C + 1} = -40.8 \times 10^{-3} \frac{4700}{10 \times 10^{-6} \times 4700 + 1} \approx -183$$

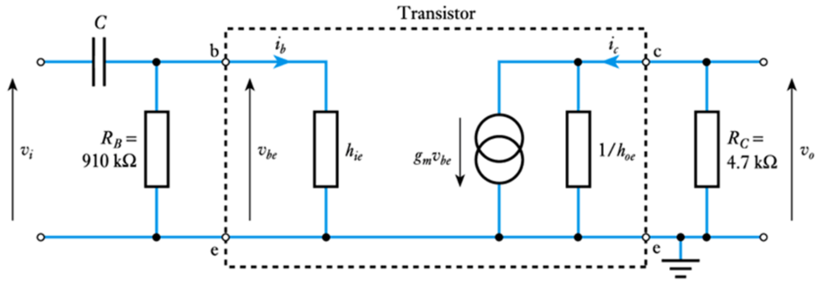
or, using the approximation

$$\text{voltage gain} \approx -g_m R_C = -40.8 \times 10^{-3} 4700 \approx -192$$

Given all the ≈, this seems a reasonable approximation

- **Input resistance**
  - from the equivalent circuit the input resistance is simply $R_B//h_{ie}$
  - Since $R_B >> h_{ie}$

$$r_i = R_B // h_{ie} \approx h_{ie} \approx 2.4\,\text{k}\Omega$$

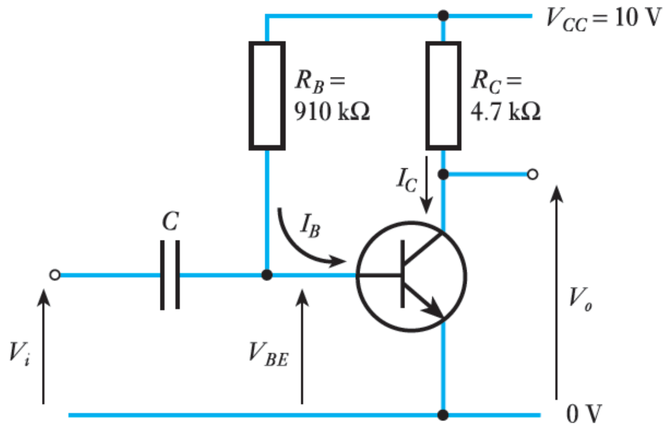


- **Output resistance**
  - from the equivalent circuit the output resistance is $R_C //(1/h_{oe})$

$$r_o = R_C //(1/h_{oe}) \approx 4700 // 100{,}000 \approx 4.5\,\text{k}\Omega$$

  - Since $R_C << 1/h_{oe}$ then $R_C//(1/h_{oe}) \approx R_C$ and therefore $r_o \approx R_C$

Summary: bipolar transistor-no feedback

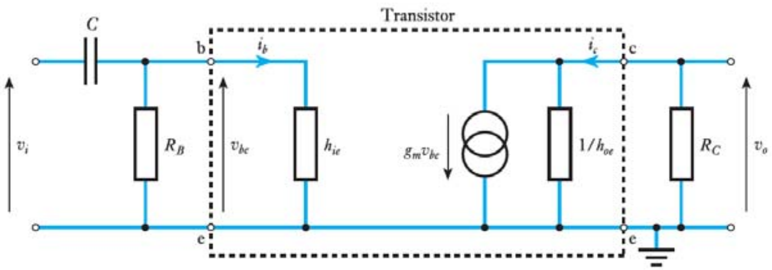


DC-large signal

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

$$I_C = h_{FE} I_B$$

$$V_o = V_{CC} - I_C R_C$$



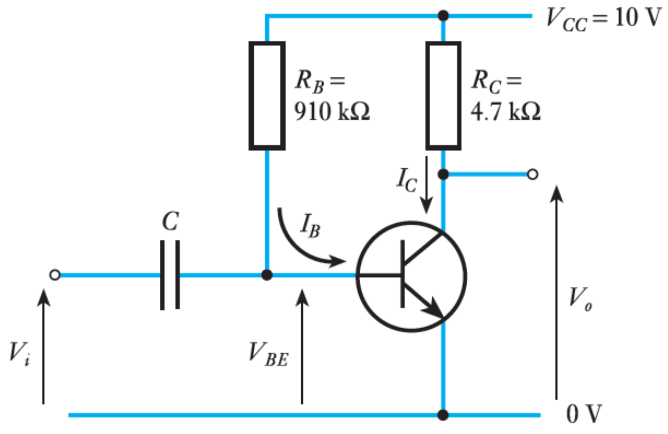
AC-small signal

$$\frac{v_o}{v_i} = -g_m \cdot \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow \frac{v_o}{v_i} \approx -g_m \cdot R_C$$

$$r_i = \frac{h_{ie}}{\frac{h_{ie}}{R_B} + 1} \qquad R_B >> h_{ie} \Rightarrow r_i \approx h_{ie}$$

$$r_o = \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow r_o = R_C$$

Problems with this circuit

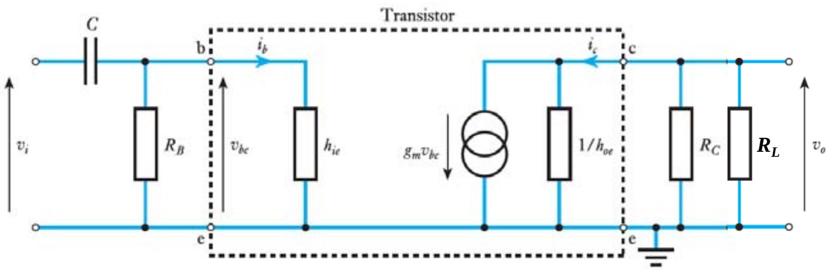


AC gains depend on:

Properties of transistor

And since $g_m \approx 40 \cdot I_C$,
$v_o/v_i \approx -40 \cdot V_{RC}$
the signal gain changes with DC operating point

R_L interacts with R_C to change gain



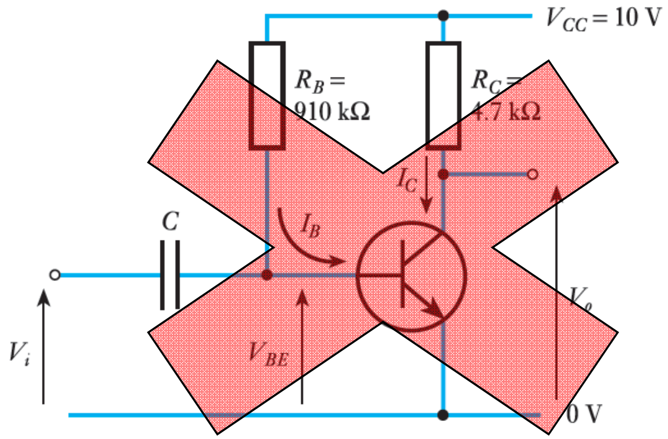
AC-small signal

$$\frac{v_o}{v_i} = -g_m \cdot \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow \quad \frac{v_o}{v_i} \approx -g_m \cdot R_C$$

$$r_i = \frac{h_{ie}}{\frac{h_{ie}}{R_B} + 1} \qquad R_B >> h_{ie} \Rightarrow \quad r_i \approx h_{ie}$$

$$r_o = \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow \quad r_o = R_C$$

Problems with this circuit



AC gains depend on:

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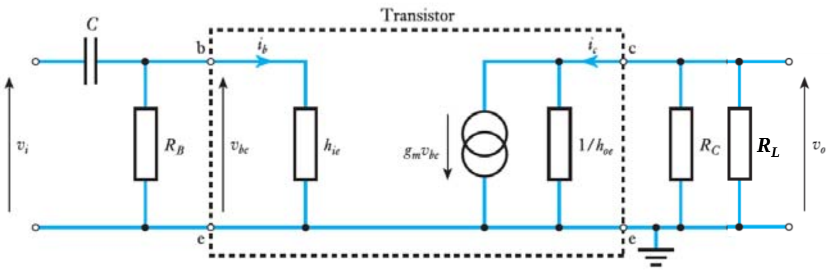


AC-small signal

$$\frac{v_o}{v_i} = -g_m \cdot \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow \qquad \frac{v_o}{v_i} \approx -g_m \cdot R_C$$

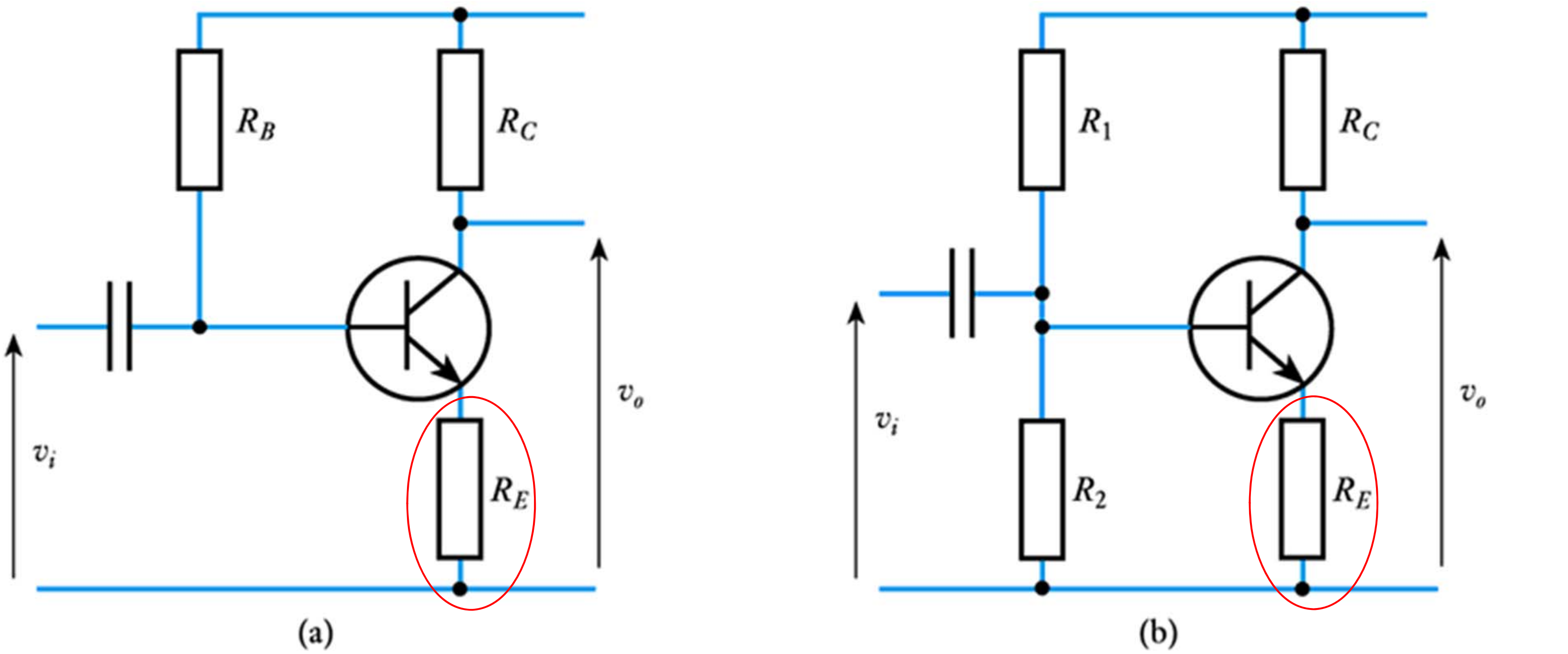
$$r_i = \frac{h_{ie}}{\frac{h_{ie}}{R_B} + 1} \qquad R_B >> h_{ie} \Rightarrow \qquad r_i \approx h_{ie}$$

$$r_o = \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow \qquad r_o = R_C$$

The use of feedback

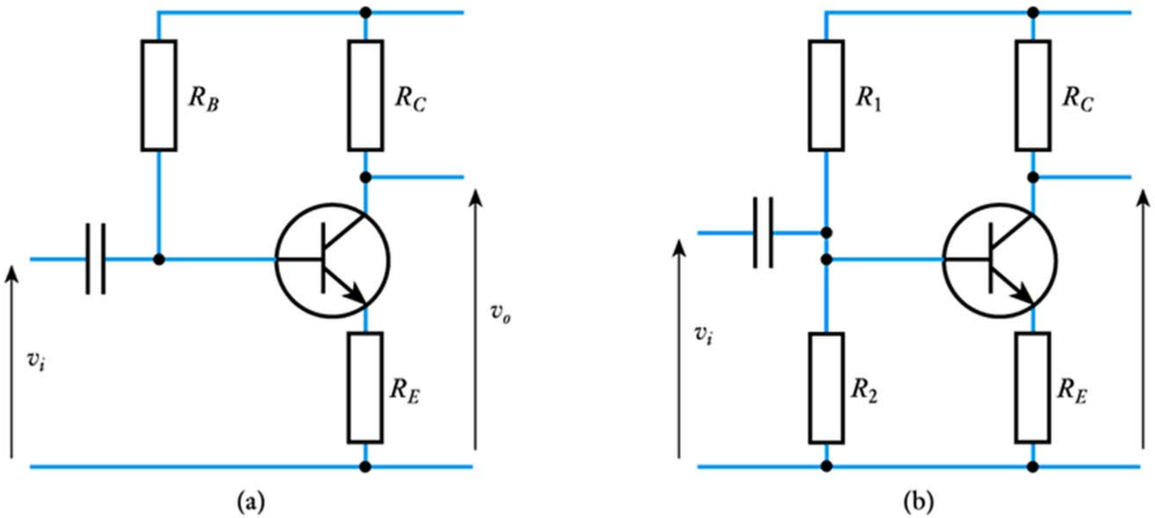
Video 19C

- Feedback can be used to overcome the effects of device variability. Consider the following circuits



How does this work?

- As $v_i \approx v_b$ rises, v_{be} forward bias increases and more i_b flows
- This causes more current, i_c, to flow
- This increases the voltage at the top of R_E *(catches up to v_i)*
- And this reduces the v_{be} forward bias
- Voltage at the top of R_E tracks $v_b \approx v_i$, and reduces gain

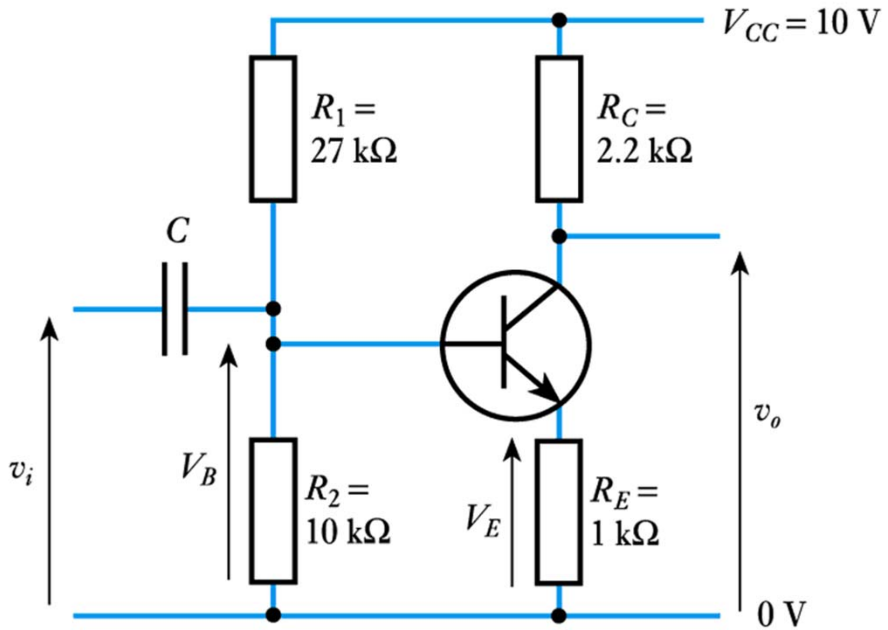


Analysis of amplifier with feedback

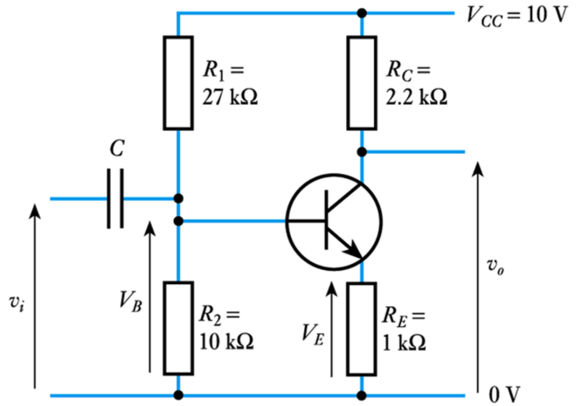
- See **Example 19.3** from course text

  Determine the quiescent voltages and currents in the following circuit
- See **Example 19.4** from course text

  Determine the small-signal behaviour of the following circuit



Results: Bipolar transistor-with feedback



DC-large signal

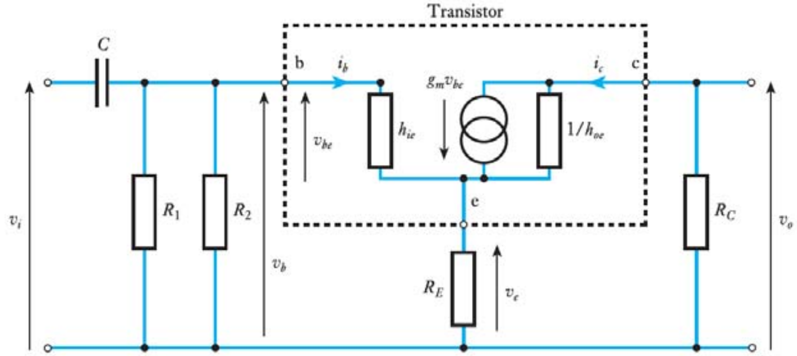
$$V_B \approx V_{CC}\frac{R_2}{R_1 + R_2} \qquad V_E = V_B - V_{BE} \qquad V_{BE} \approx \text{constant} \approx 0.7\text{V}$$

$$I_B << I_C \approx I_E$$

$$I_E \approx I_C = \frac{V_E}{R_E}$$

$$V_o = V_{CC} - I_C R_C$$

Gain, r_i and r_o only depend on passive components



AC-small signal

$$\frac{v_o}{v_i} = -\frac{R_C}{R_E + \frac{1}{g_m}} \qquad R_E >> \frac{1}{g_m} \qquad \Rightarrow \frac{v_o}{v_i} \approx -\frac{R_C}{R_E}$$

$$r_b = h_{ie} + \left(h_{fe} + 1\right) R_E \qquad h_{fe} \cdot R_E >> h_{ie} >> 1 \Rightarrow r_b \approx h_{fe} \cdot R_E$$

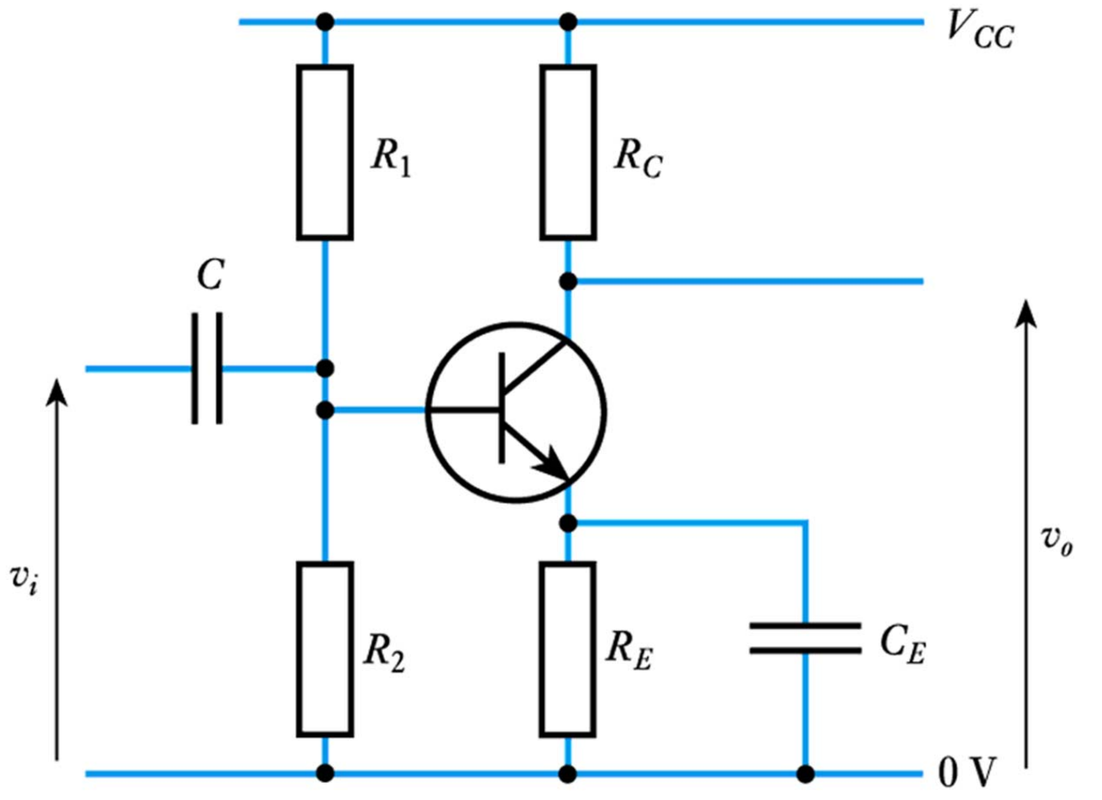
$$r_i = R_1 \parallel R_2 \parallel r_b \qquad r_b >> R_1 \approx R_2 \Rightarrow r_i \approx \frac{R_1 \cdot R_2}{R_1 + R_2}$$

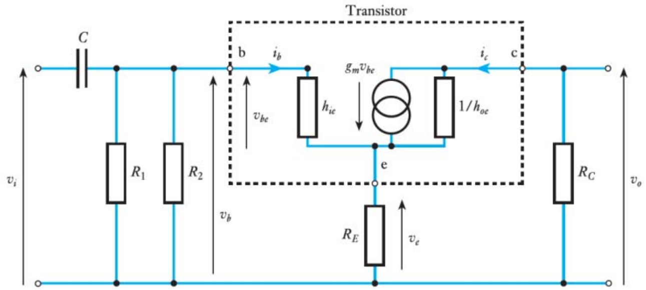
$$r_o = R_C \parallel \left(\frac{1}{h_{oe}} + R_E\right) \qquad R_C << \frac{1}{h_{oe}} + R_E \Rightarrow r_o \approx R_C$$

Reduces the amount of AC negative feedback while maintaining DC feedback.
This *increases the small-signal gain of the circuit* but *does not affect the DC feedback*,
This provides stability to the bias conditions of the circuit

Use of a decoupling capacitor

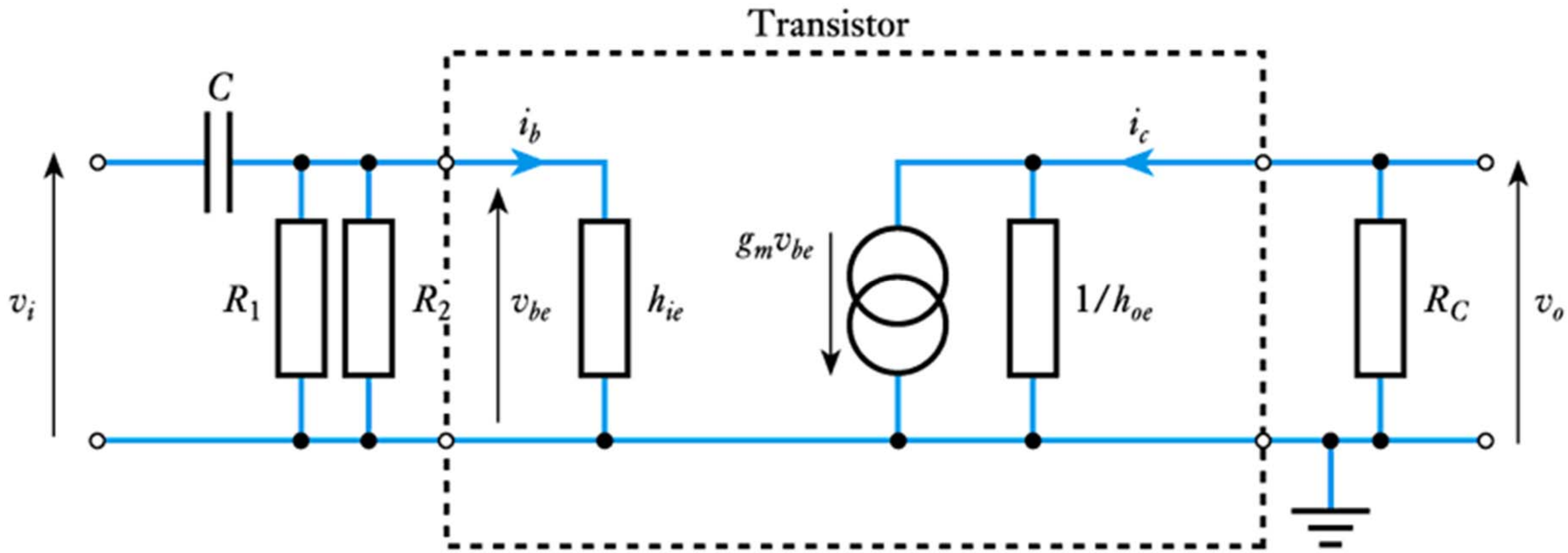
- A decoupling capacitor removes small-signal feedback





Small signal equivalent circuit without coupling capacitor

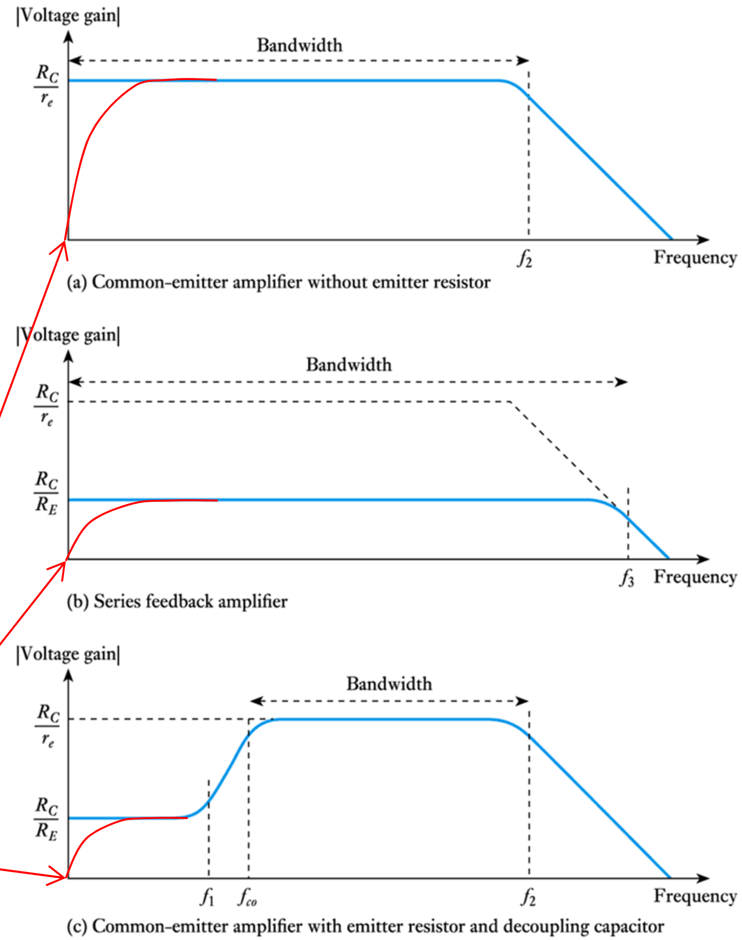
- Small-signal equivalent circuit of an amplifier using a decoupling capacitor (Shorts out R_E in signal band)



Remember $r_e = 1/g_m$ and gain was $g_m \cdot R_c$

- A comparison of the frequency responses of various amplifiers
  - for simplicity, the figure shows the responses of amplifiers that are *not* fitted with coupling capacitors

With an ac coupling capacitor



Summary

- DC and small-signal (AC) gains no feedback
  - Gain depends on characteristics of specific transistor
- DC and small-signal gains with negative feedback
  - Small-gain but depends on stable passive resistors
- Decoupling capacitor
  - Claw back some of the lost gain within the signal band