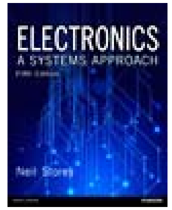
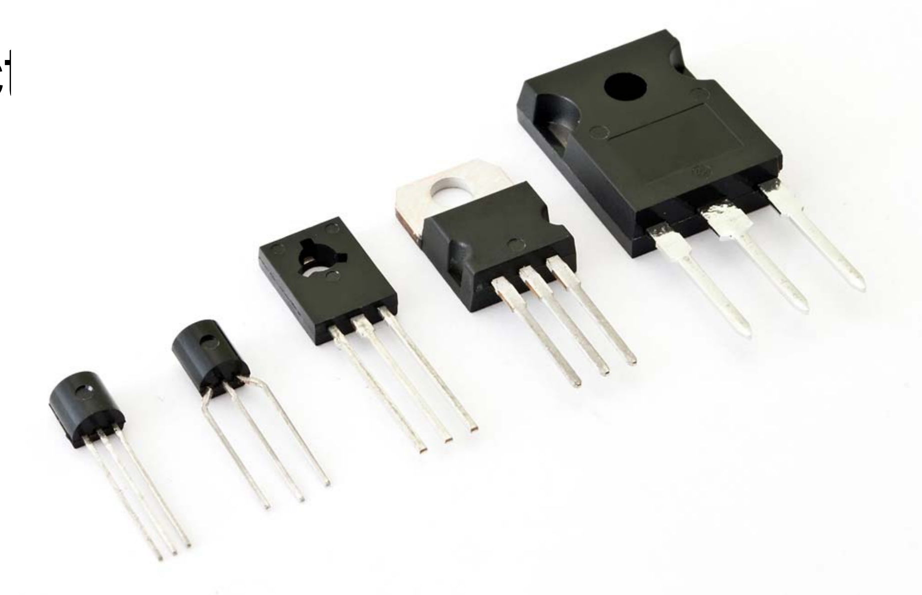


Chapter 18

Last time: Field-effect transistors

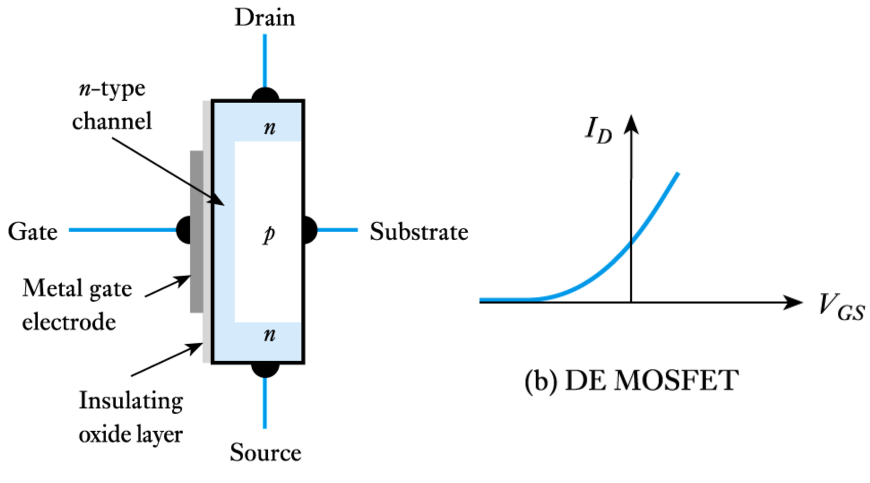
- Introduction
- An overview of field-effect transistors
- Insulated-gate field-effect
- Junction-gate field-effect
- FET characteristics
- FET amplifiers
- Other FET applications
- FET circuit examples



N-channel FET transistors

DE-MOSFET

The more $V_{GG} < V_{SS} = 0V$
repels electrons from Gate
deplete width of n-channel
less current flows $D \rightarrow S$

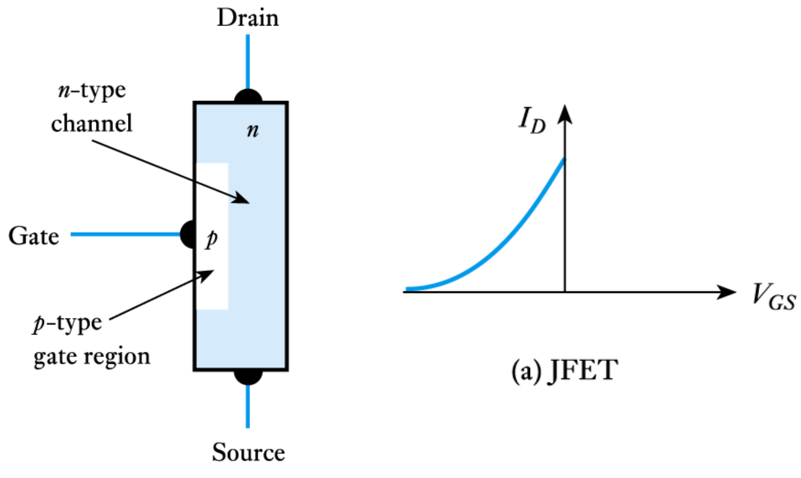


(a) n-channel

(b) DE MOSFET

JFET

The more $V_{GG} < V_{SS} = 0V$
increase the G-S reverse bias
increase width of depletion layer
less current flows $D \rightarrow S$



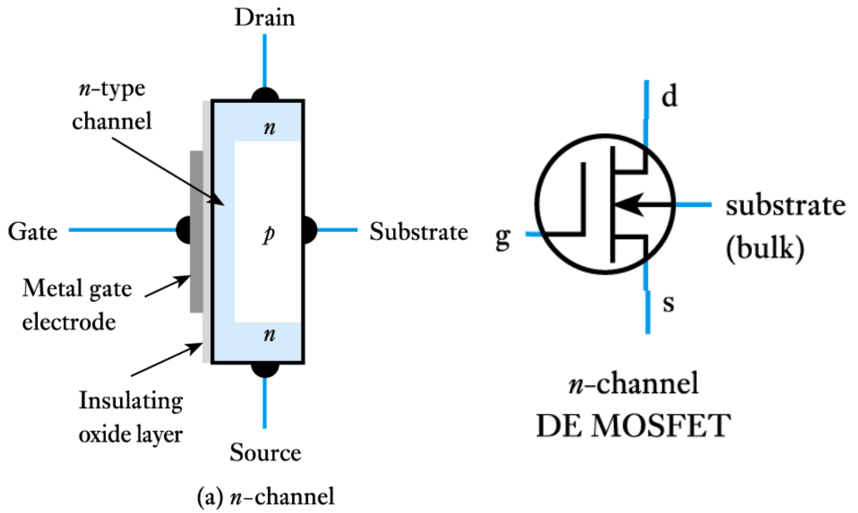
(a) n-channel

(a) JFET

N-channel FET transistors

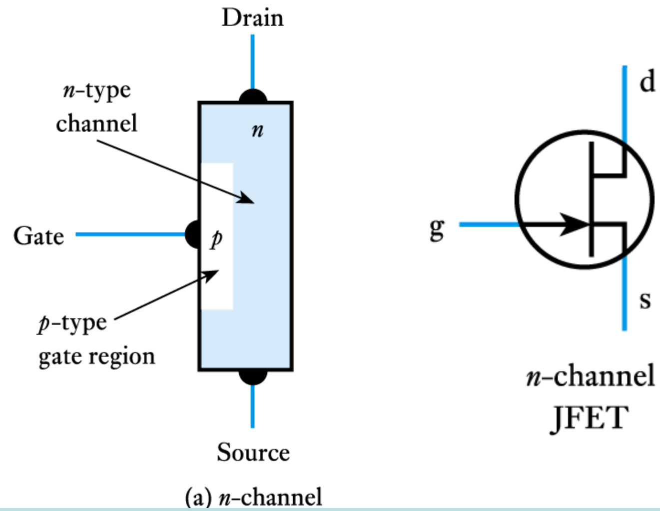
DE-MOSFET

The more $V_{GG} < V_{SS}$ = 0V
repels electrons from Gate
deplete width of n-channel
less current flows D $\rightarrow$ S

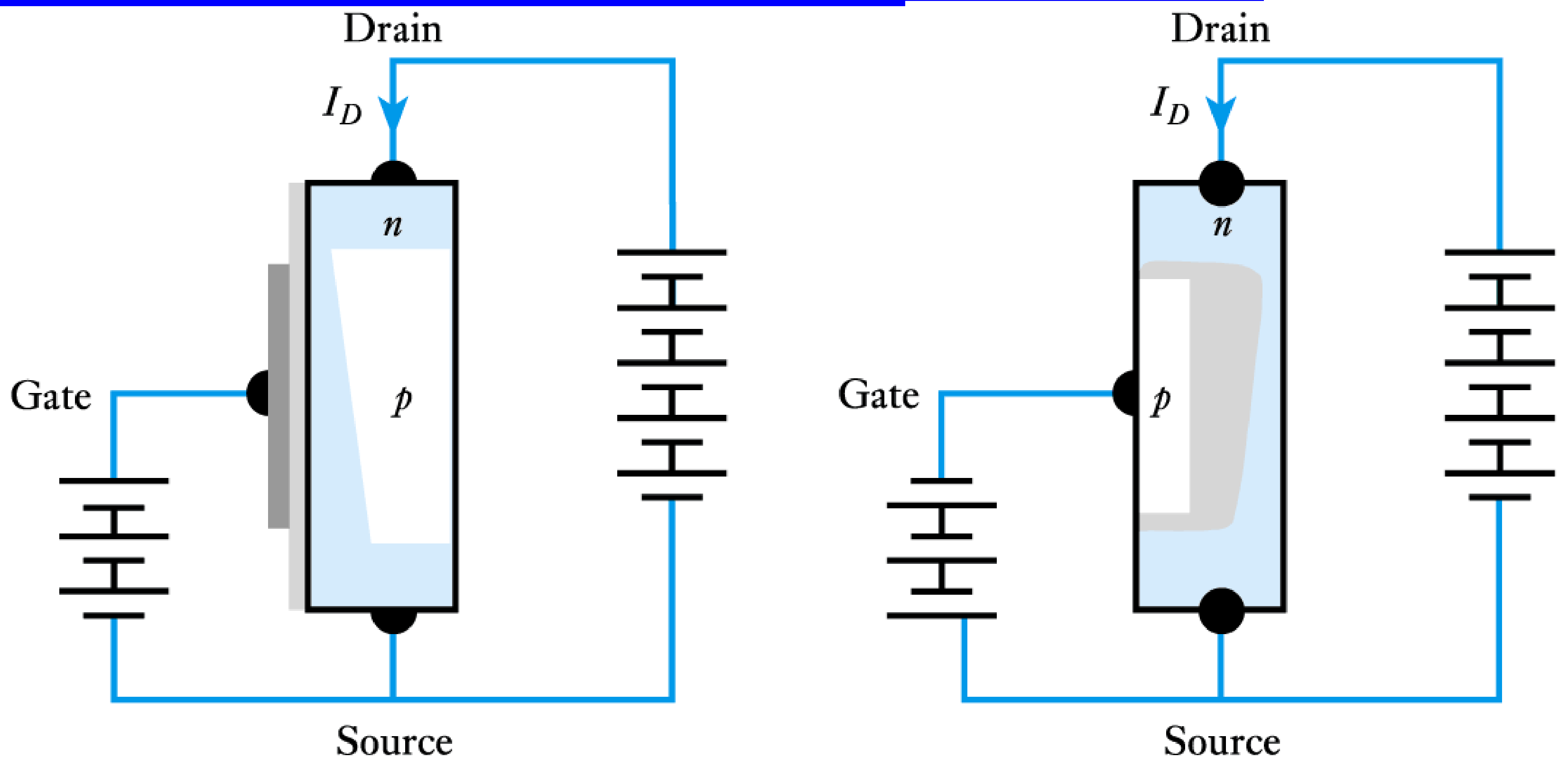


JFET

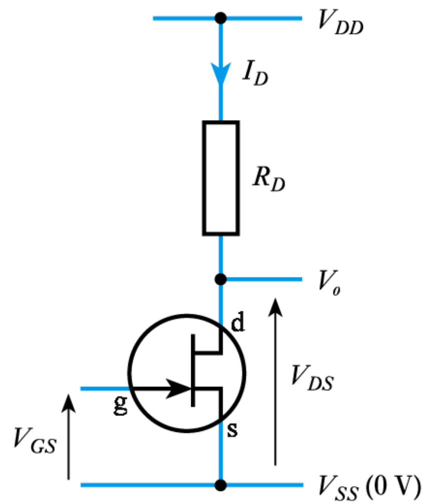
The more $V_{GG} < V_{SS}$ = 0V
increase the G-S reverse bias
increase width of depletion layer
less current flows D $\rightarrow$ S



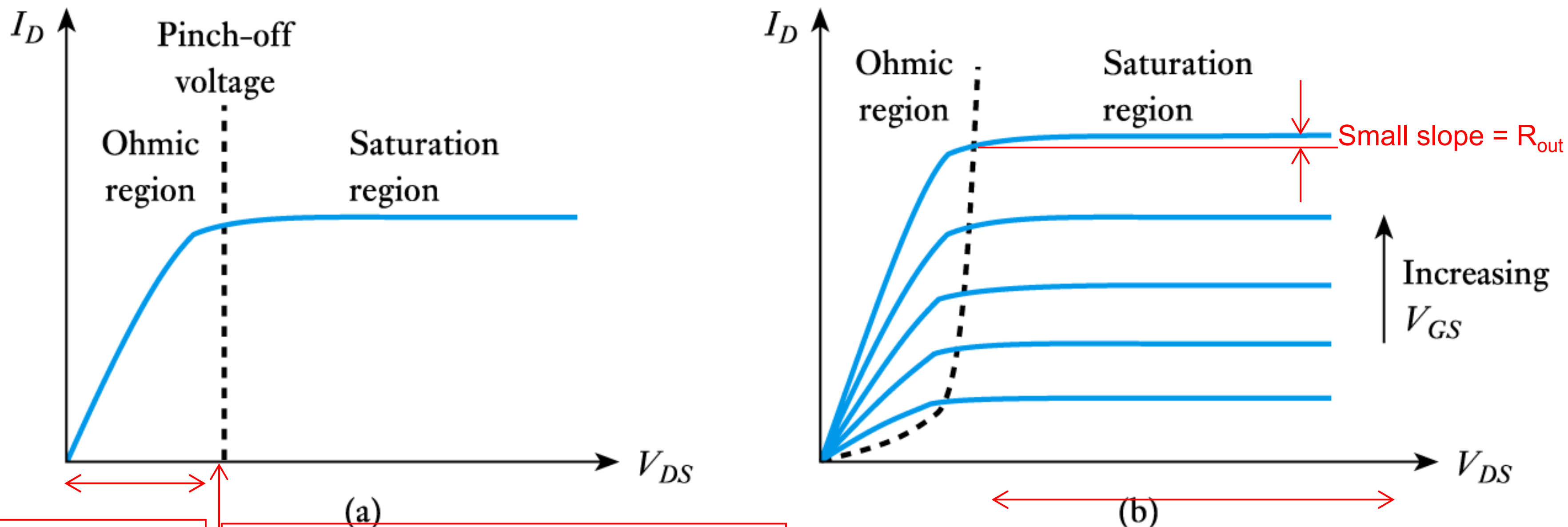
Effectively get a bias set up between the potential on the drain and the gate.
MOSFET $V_D > V_G \rightarrow$ depleted channel, $V_G > V_S \rightarrow$ enhanced channel
JFET $V_{GD} > V_{GS} \rightarrow$ larger reverse bias at drain end $\rightarrow$ larger depletion region
Tapers and "pinches off" the channel at high V_{DS}.



(a) MOSFET (b) JFET



▪ FET output characteristics

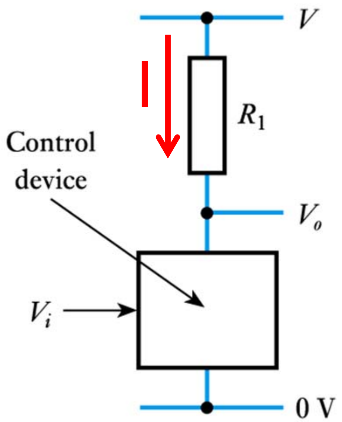


Here channel has resistance set by V_{GS}

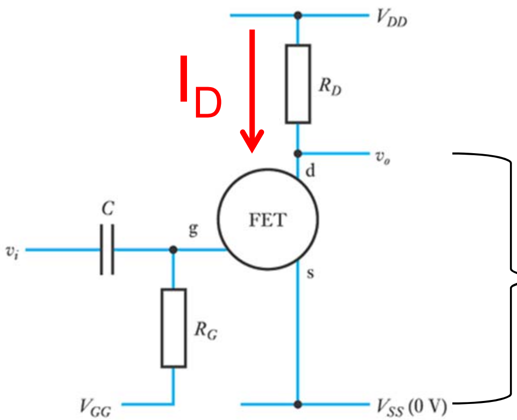
Above here the channel thickness is ≈ 0 at drain

Here I_D ~independent of the applied voltage & controlled by V_{GS}

Gain of device



A simple amplifier



(d) A generic FET circuit

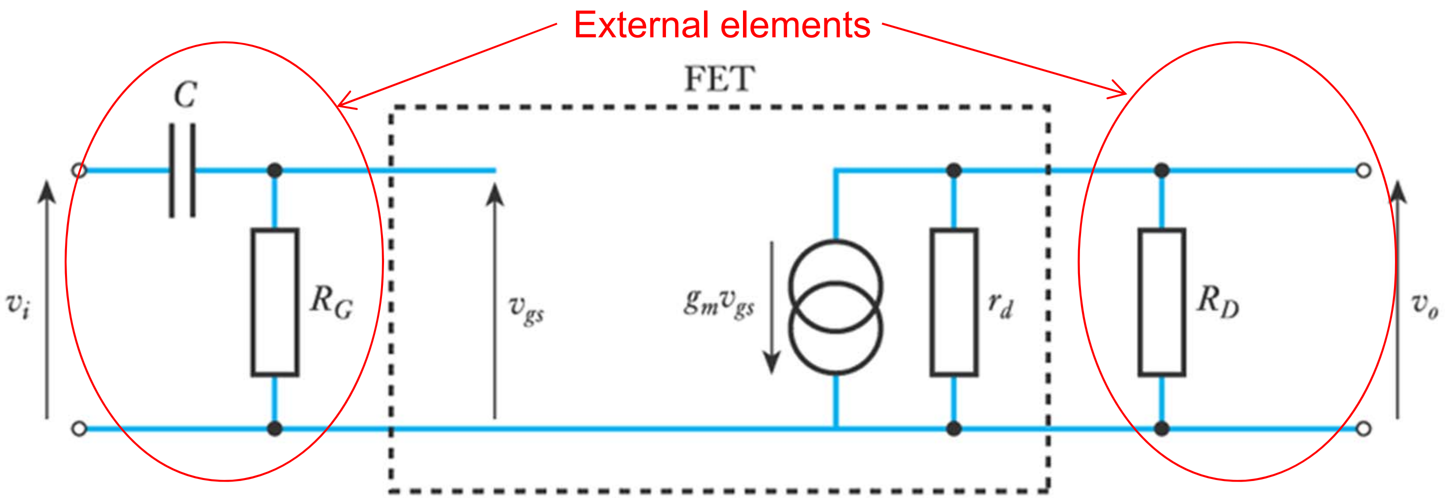
So, the FET is the control device and

$V_{output} = V_{DD} - I_D \cdot R_D$

- When $V_i = V_{GS}$ increases, I_D increases
- Then most of the voltage, V_{DD}, drops across R_D
  - Thus, Vo gets smaller
- Inverting amplifier
- V_{GS} decreases $\Rightarrow$ I_D decreases $\Rightarrow$ V_o increases

Equivalent circuit of a FET amplifier

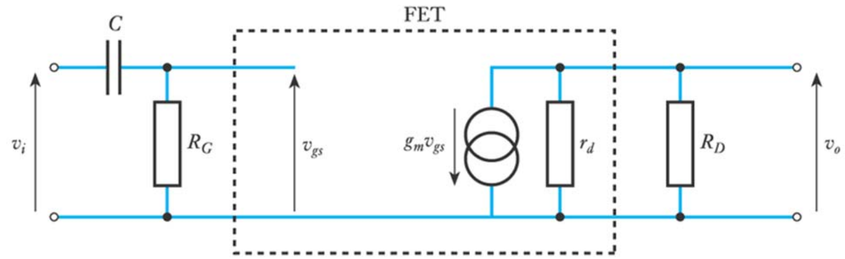
Video 18B



- This circuit can represent any of the FET amplifiers above (by choosing an appropriate value of R_G)
  - This is a **small signal-equivalent circuit**
  - Note that R_D goes to *ground*, since the supply voltage V_{DD} (and any DC voltage) is a virtual earth point for small signals (small signal $\Rightarrow$ AC signals)

Small-signal voltage gain

- From the equivalent circuit we can derive the small-signal voltage gain



$$\text{V = I*R} \Rightarrow \quad v_o = -g_m v_{gs}(r_d \,//\, R_D)$$

$$= -g_m v_i (r_d \,//\, R_D)$$

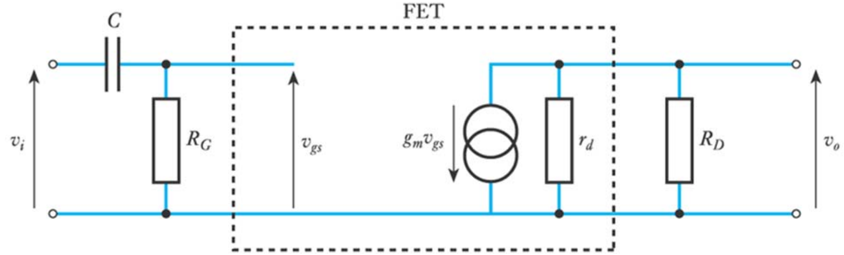
therefore

$$\frac{v_o}{v_i} = -g_m (r_d \,//\, R_D)$$

- Also

$$r_i \approx R_G \qquad\qquad r_o \approx r_d \,//\, R_D$$

- In many cases $r_d >> R_D$ so r_d can often be ignored
- If this is the case



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

$$r_i \approx R_G$$

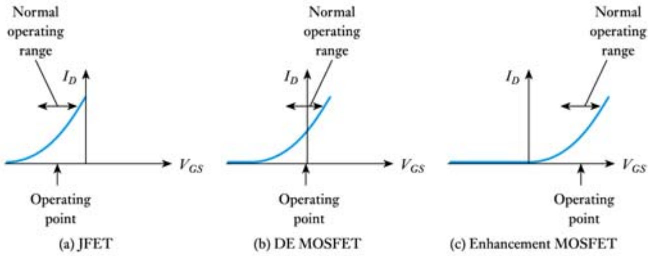
$$r_o \approx R_D$$

Biasing considerations

- The biasing arrangement determines the operation of the circuit
  – This is its **quiescent** state
- The quiescent output voltage $v_{o(quies)}$ is given by

$$V_{o(quies)} = V_{DD} - I_{D(quies)} R_D$$

- However, since the FET is not linear, determining the quiescent conditions is not straightforward

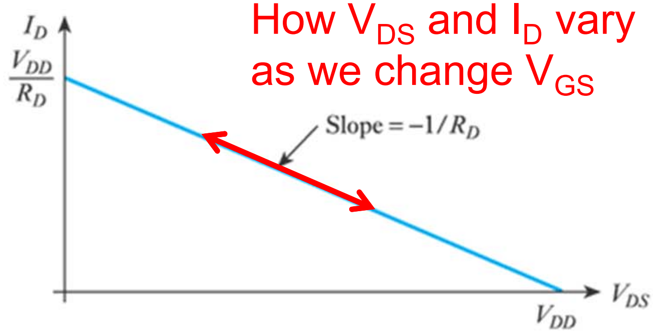


$V_{output} = V_{DS} = V_{DD} - I_D \cdot R_D$

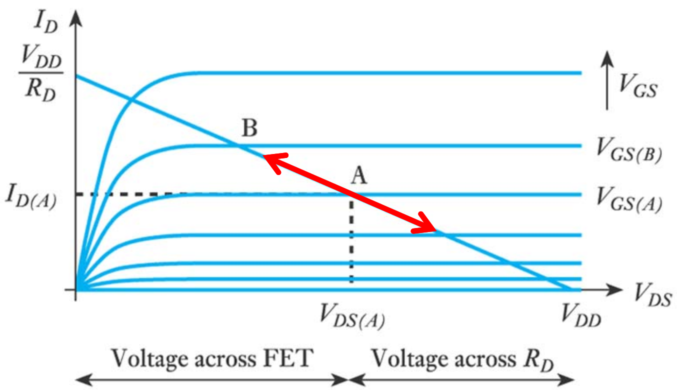
When $I_D = 0 \Rightarrow V_{DS} = V_{DD}$

When $V_{DS} = 0 \Rightarrow V_{DD} = I_D \cdot R_D$

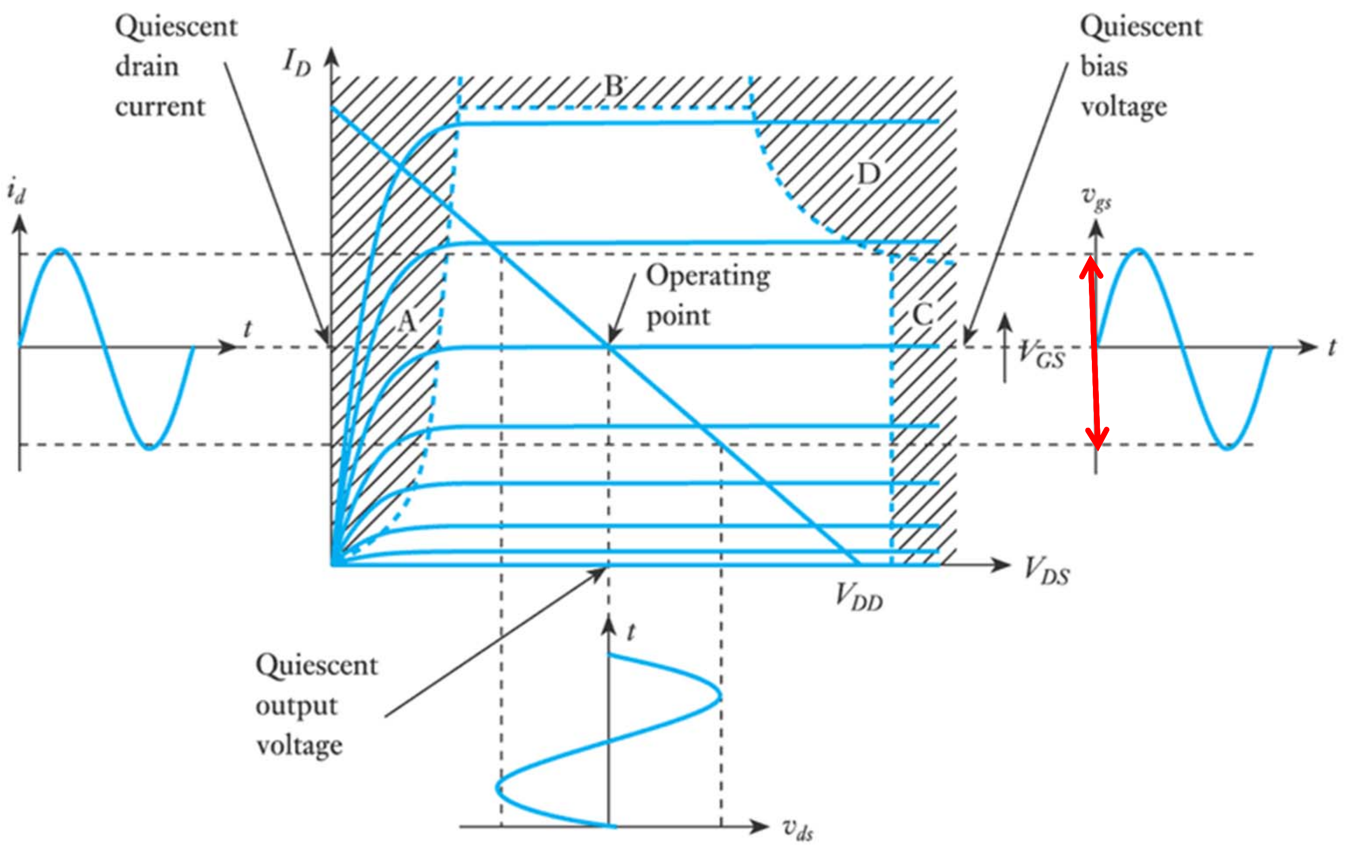
- Bias to correct operation point using a **load line**



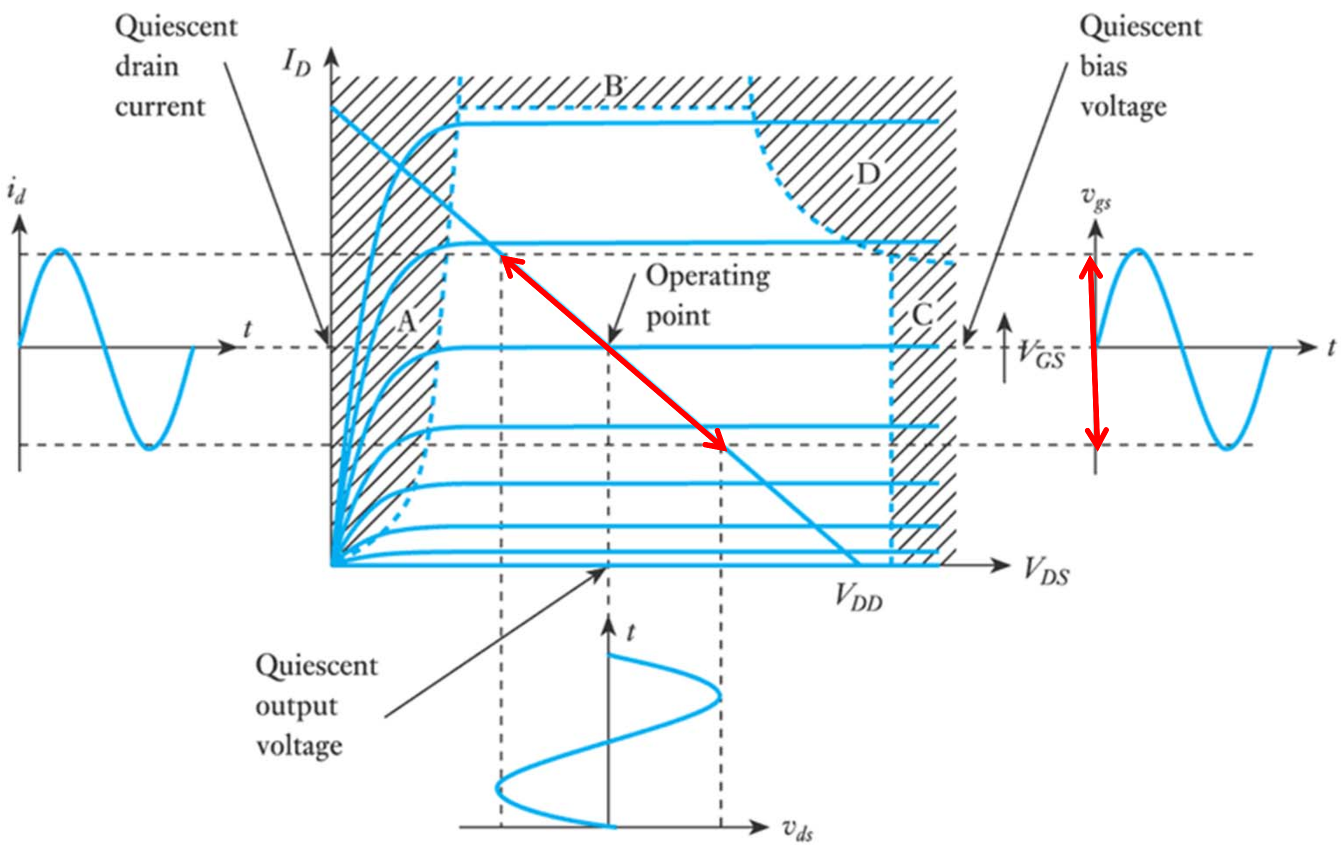
How V_{DS} and I_D vary as we change V_{GS}

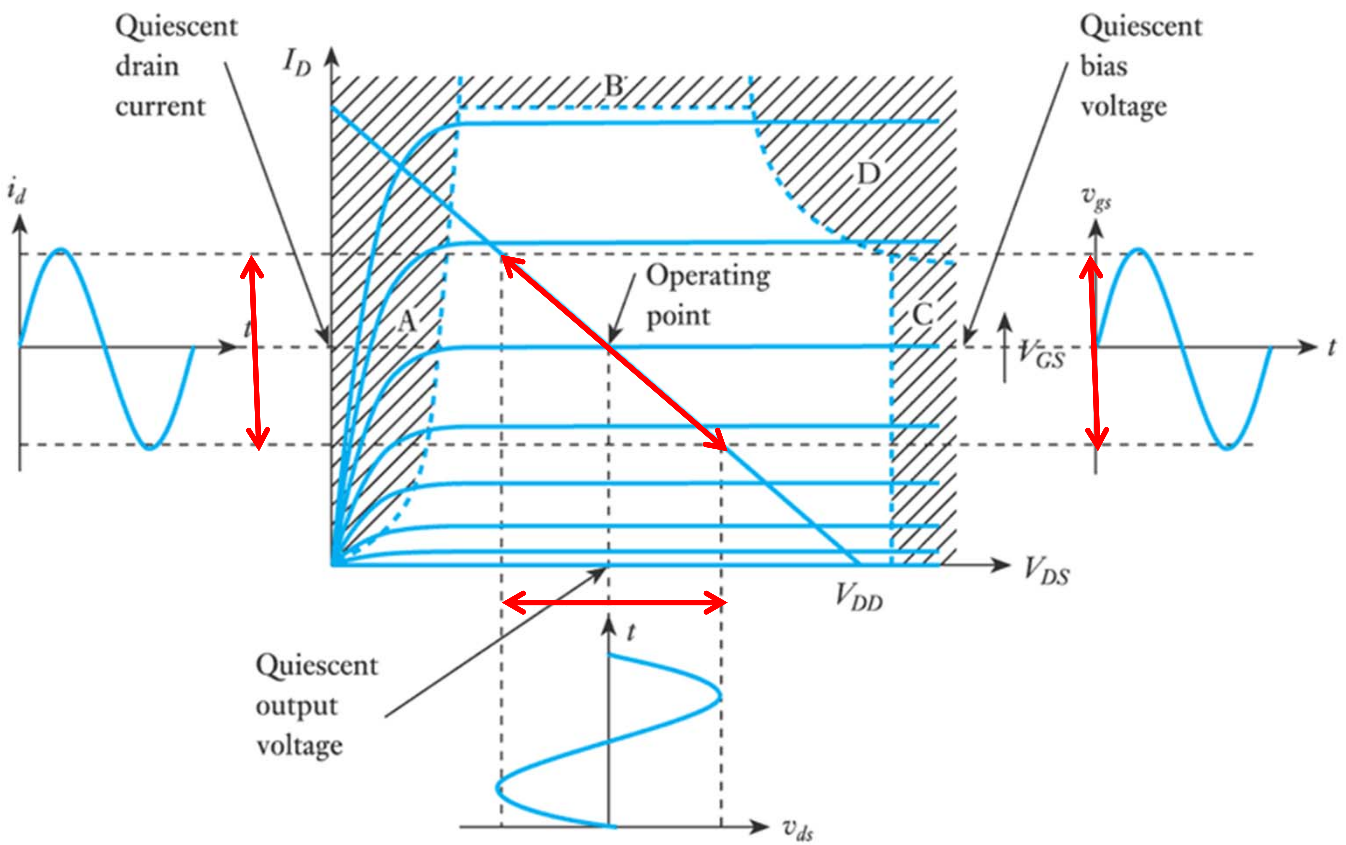


V_O



Quiescent drain current
I_D
B
D
i_d
t
A
Operating point
C
Quiescent bias voltage
v_{gs}
V_{GS}
t
V_{DS}
V_{DD}
Quiescent output voltage
t
v_{ds}

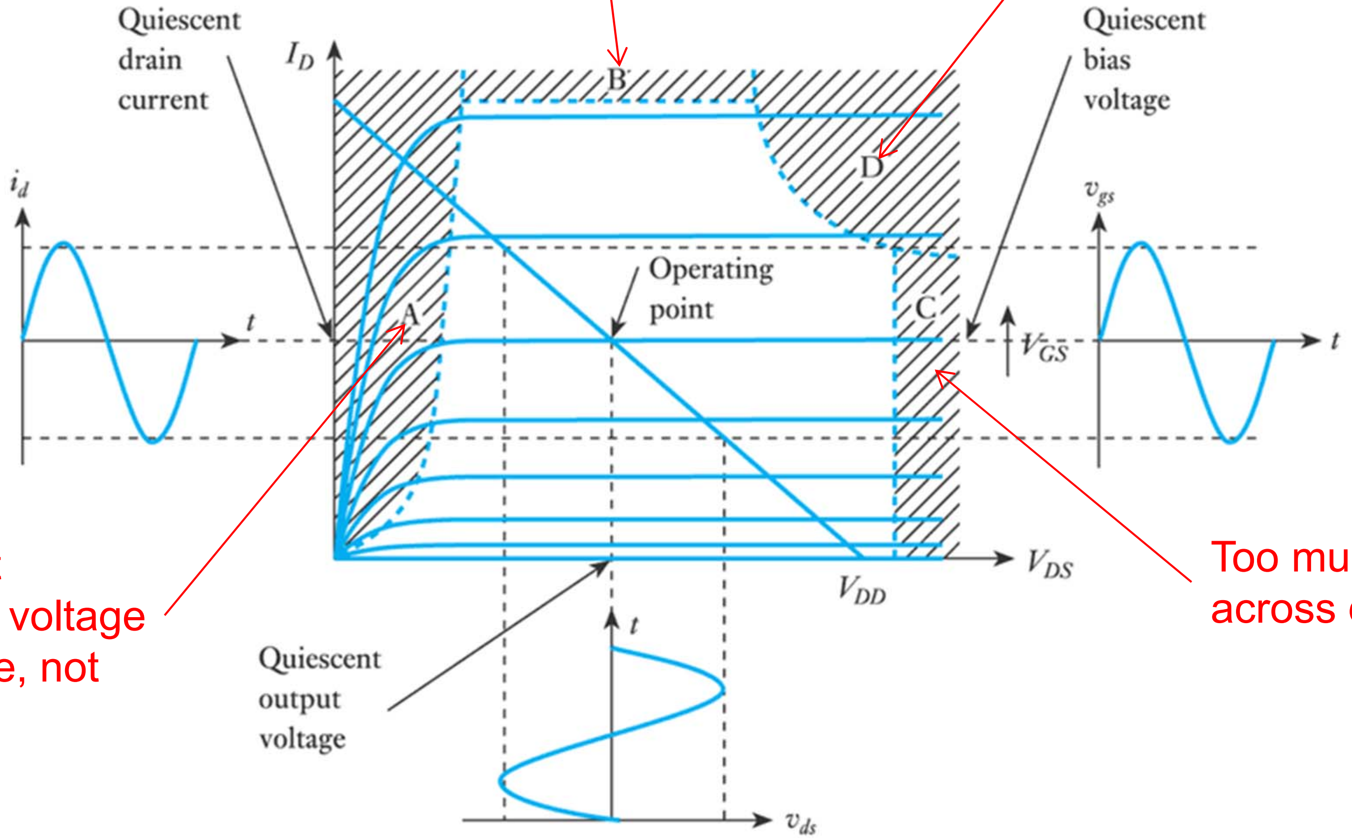

Quiescent
drain
current
I_D
B
D
Quiescent
bias
voltage
i_d
v_{gs}
t
Operating
point
A
C
V_{GS}
t
V_{DS}
V_{DD}
Quiescent
output
voltage
t
v_{ds}



Quiescent
drain
current
I_D
B
D
A
C
Operating
point
Quiescent
bias
voltage
i_d
t
v_{gs}
t
V_{GS}
V_{DS}
V_{DD}
Quiescent
output
voltage
t
v_{ds}

Too much current or V_{GS} now forward biased

Too much power dissipated in device ($P = V_{DS} \cdot I_D$)



Drain current controlled by voltage across device, not gate voltage

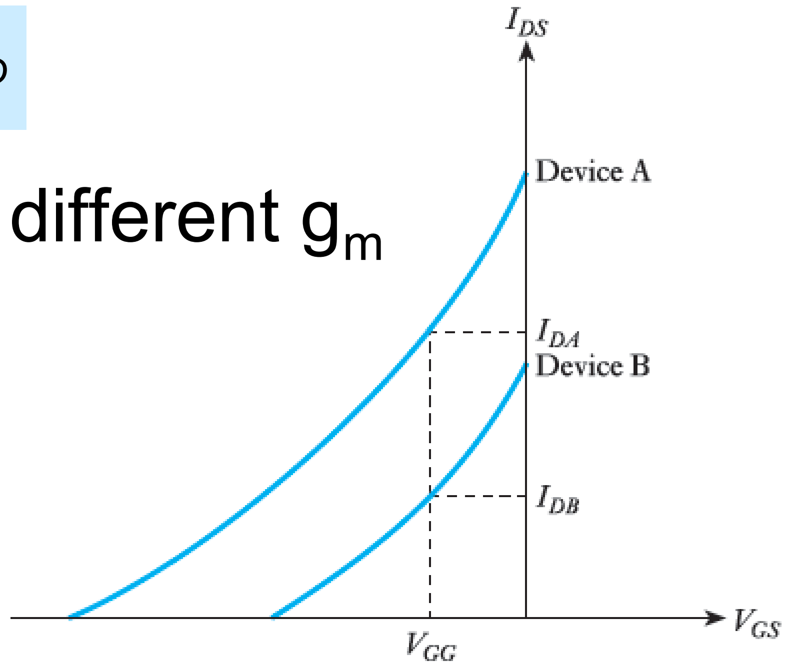
Too much voltage across device

Device variability

- FETs, like all active devices, suffer from variability

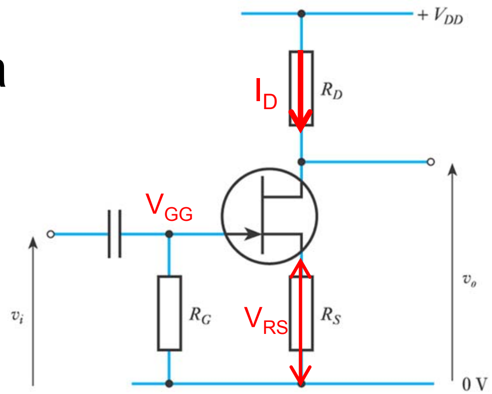
$$\text{voltage gain} = \frac{v_o}{v_i} \approx -g_m R_D$$

- Different devices have different g_m



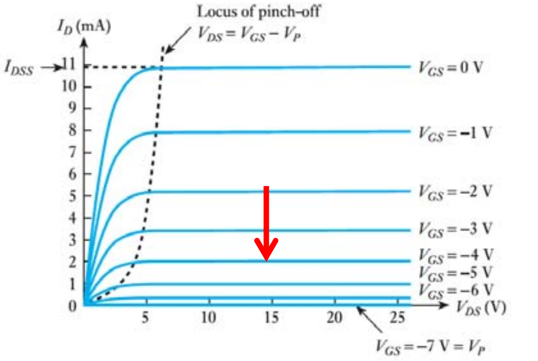
Get a large spread in quiescent current between A and B

- The effects of device variability on the quiescent conditions of a circuit can be tackled using feedback
  - for example, the use of **'automatic' bias**

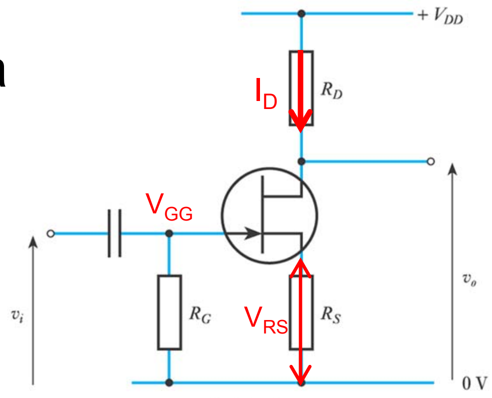


(a) Circuit

I_D increases
$V_{RS} = I_D \cdot R_S$ increases
V_{GG} the same so
V_{GS} more negative
So I_D decreases

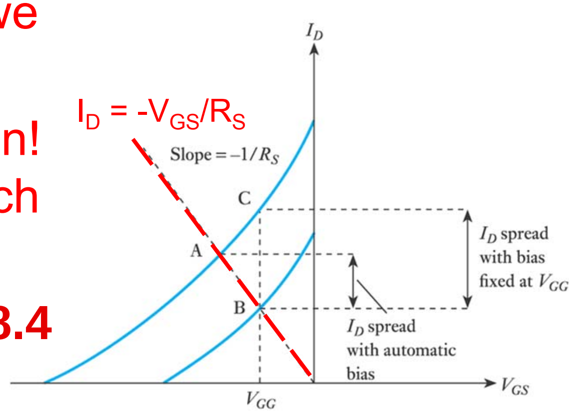


- The effects of device variability on the quiescent conditions of a circuit can be tackled using feedback
  - for example, the use of **‘automatic’ bias**
  - As we change V_{GS} we move along the $-1/R_S$ line when we have feedback
  - Stable, but large loss in gain! (I_D does not change as much for a change in V_{GS})
  - see **Examples 18.3 and 18.4** of the course text

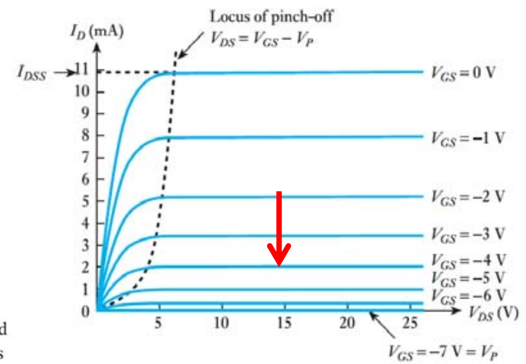


(a) Circuit

I_D increases
$V_{RS} = I_D{\cdot}R_S$ increases
V_{GG} the same so
V_{GS} more negative
So I_D decreases



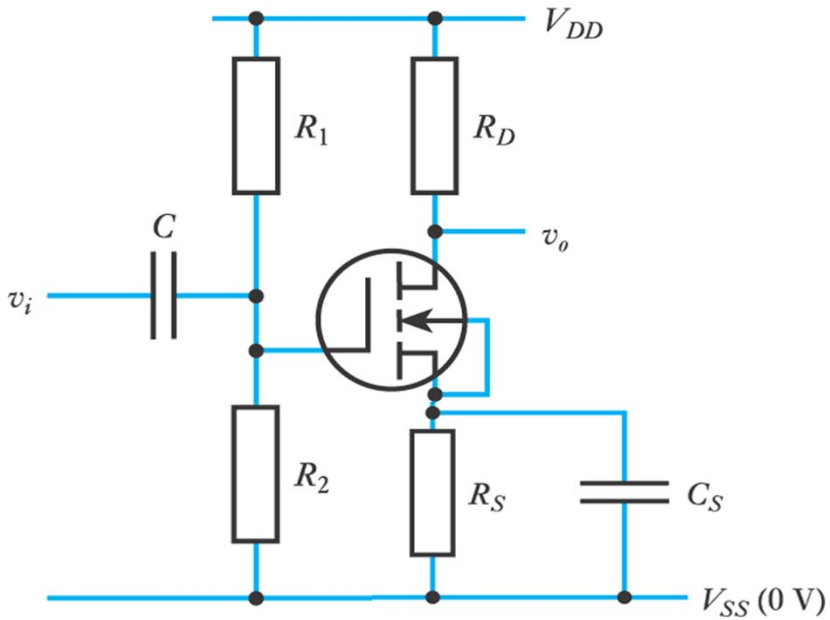
(b) Effect on drain current



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



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

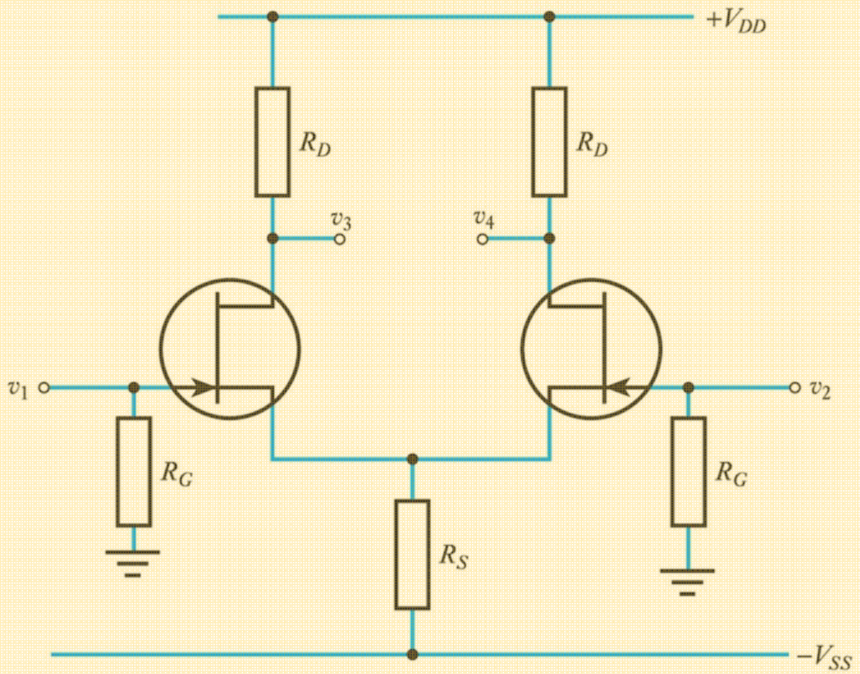
$$r_i \approx R_1 // R_2$$

$$r_o \approx R_D$$

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

Differential amplifiers (INFORMATION ONLY)

- A simple differential amplifier using JFETs
  - this is termed a **long-tailed pair** amplifier

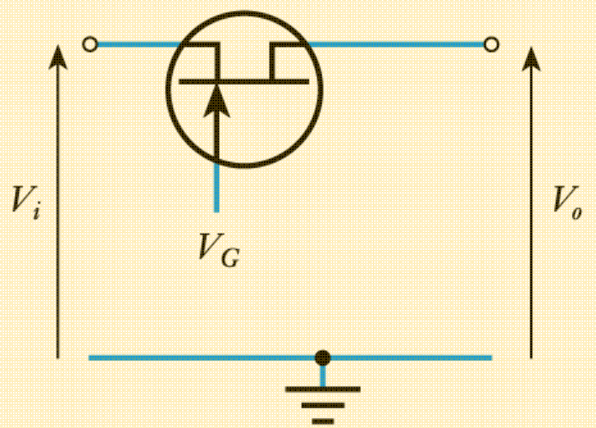


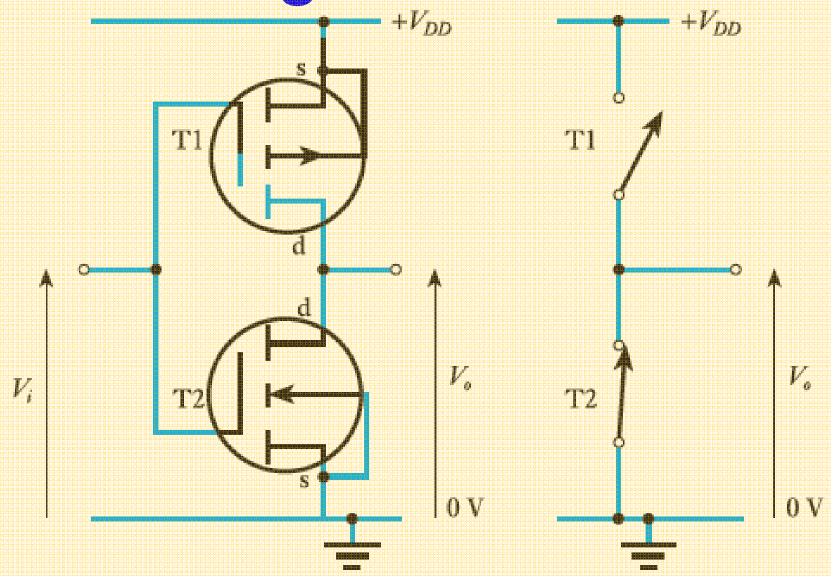
$$\text{voltage gain} = \frac{v_o}{v_i} = \frac{v_3 - v_4}{v_1 - v_2} \approx -g_m R_D$$

Front end of a FET op-amp

Analogue/digital switch (INFORMATION ONLY)

- A FET as an analogue switch or logical switch





(a) Circuit (b) Switch equivalent

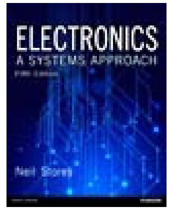
$V_G = 0$, Device on & I_D large

$V_G << 0$, Device off & $I_D \approx 0$

V_i close to 0, T_2 off, T_1 on & $V_o \approx V_{DD}$

V_i close to V_{DD}, T_2 on, T_1off & $V_o \approx 0$

CMOS logic



Video 18D Further Study

Further Study

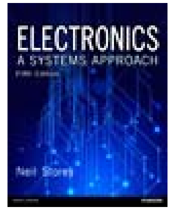
- The Further Study section at the end of Chapter 18 looks at the use of FETs as switches.
- The problem here is to design an amplifier in which the gain can be set to 1, 10 or 100 by pressing one of three push-buttons.

- Use the techniques described earlier to produce this arrangement and then watch the video.

Key points

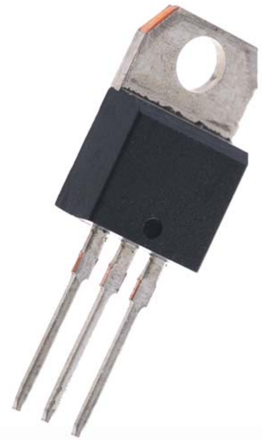
- FETs are widely used in both analogue and digital circuits
- They have high input resistance and small physical size
- There are two basic forms of FET: MOSFETs and JFETs
- MOSFETs may be divided into DE and Enhancement types
- In each case the gate voltage controls the current from the drain to the source
- The characteristics of the various forms of FET are similar except that they require different bias voltages
- FETs can be used in a range of amplifier configurations
- FETs can be also used to produce other circuit applications

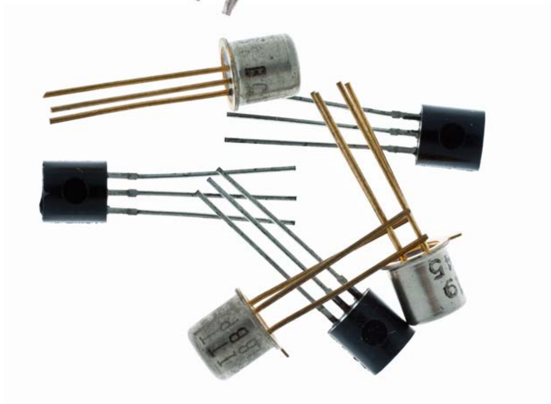
- Questions?

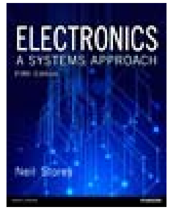


Bipolar junction transistors

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





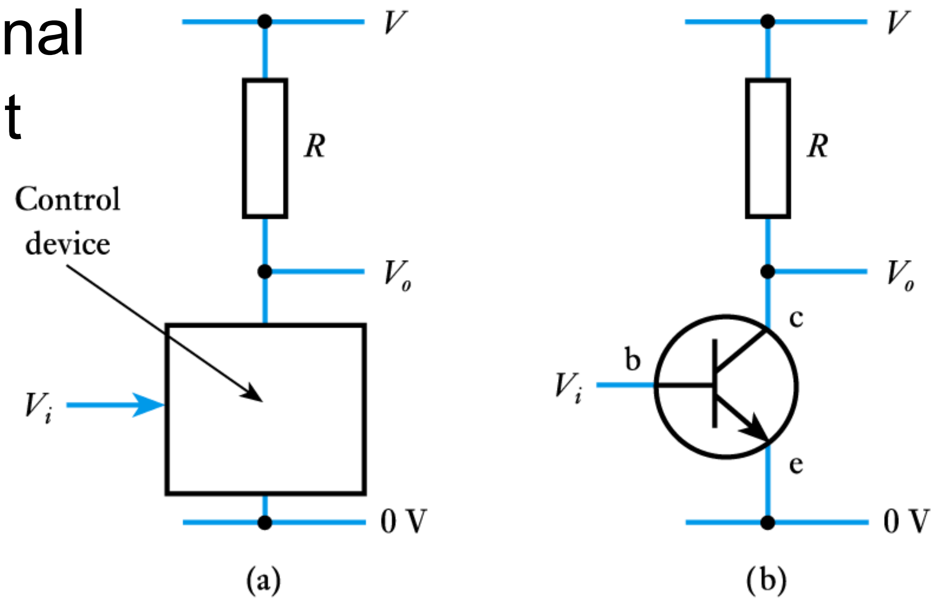


Introduction

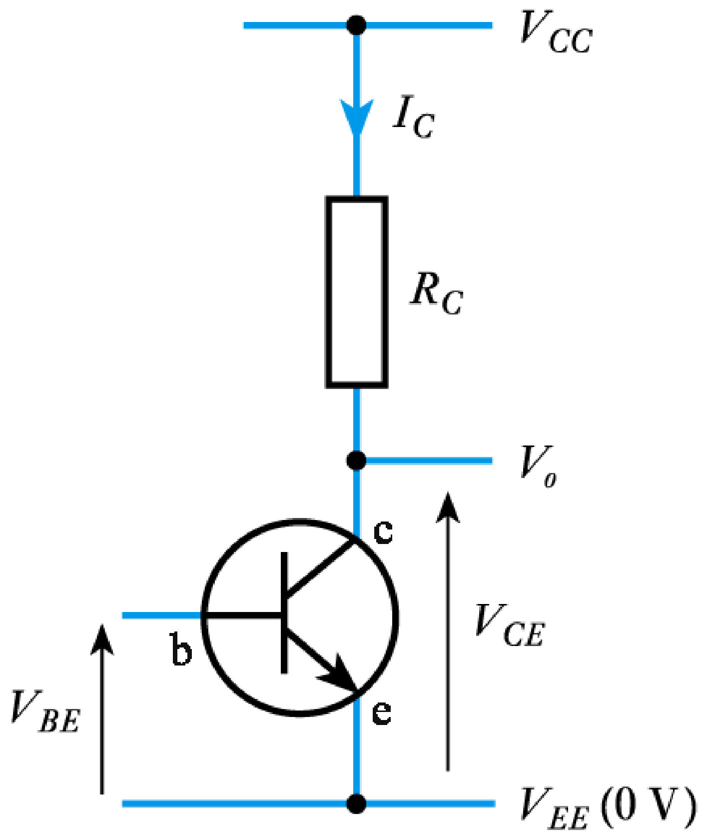
- Bipolar transistors are one of the main 'building-blocks' in electronic systems
- They are used in both analogue and digital circuits
- They incorporate two *pn* junctions and are sometimes known as **bipolar junction transistors** or **BJTs**
- Here will refer to them simply as **bipolar transistors**

An overview of bipolar transistors

- While control in a FET is due to an electric *field*, control in a bipolar transistor is generally considered to be due to an electric *current*
  - Current into one terminal determines the current between two others
  - As with a FET, a bipolar transistor can be used as a 'control device'



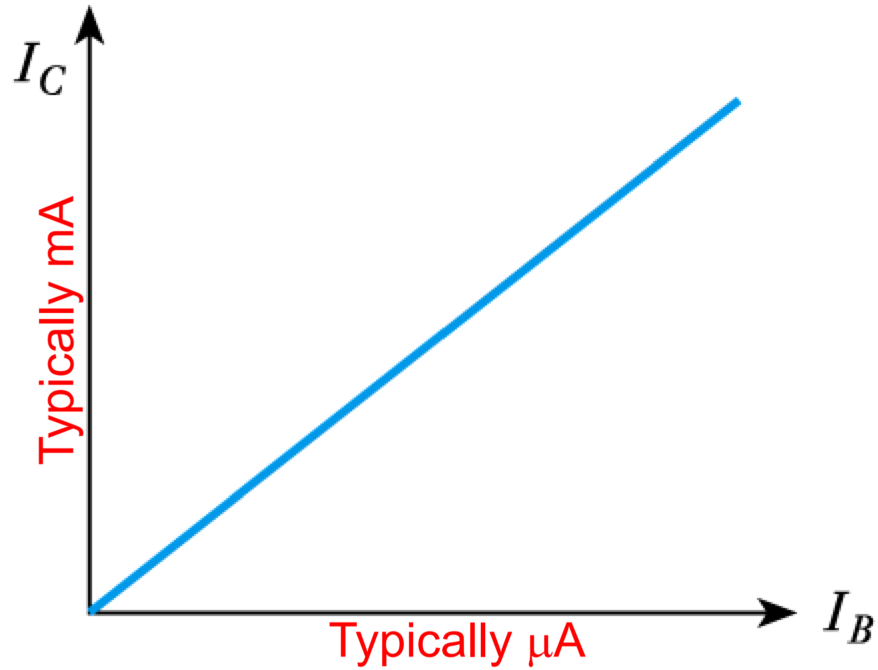
- **Notation**
  - bipolar transistors are 3 terminal devices
    - collector (c)
    - base (b)
    - emitter (e)
  - the base is the control input
  - diagram illustrates the notation used for labelling voltages and currents



Why 2-types of transistors

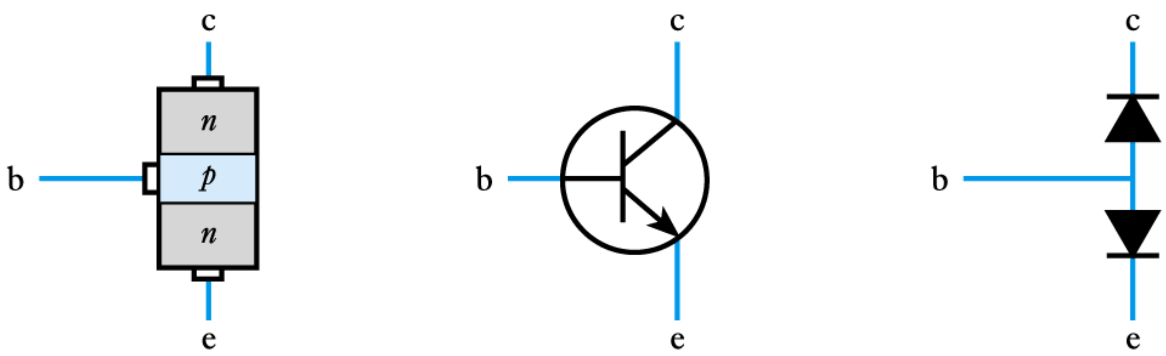
	Field Effect Transistor (FET)	Bipolar Junction Transistor (BJT)
1	Low voltage gain	High voltage gain
2	High current gain	Low current gain
3	Very high input impedance	Low input impedance
4	High output impedance	Low output impedance
5	Low noise generation	Medium noise generation
6	Fast switching time	Medium switching time
7	Easily damaged by static	Robust
8	Some require an input to turn it “OFF”	Requires zero input to turn it “OFF”
9	Voltage controlled device	Current controlled device
10	Exhibits the properties of a Resistor	
11	More expensive than bipolar	Cheap
12	Difficult to bias	Easy to bias

- Relationship between the collector current and the base current in a bipolar transistor
  - characteristic is approximately linear
  - magnitude of collector current is generally many times that of the base current
  - the device provides **current gain**

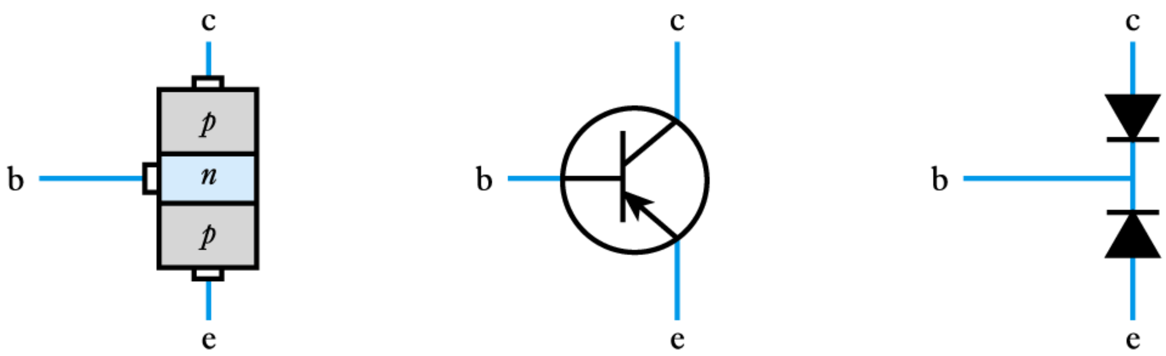


Construction

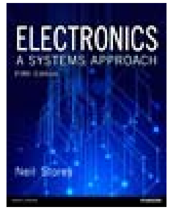
- two polarities: *npn* and *pnp*



(a) An *npn* transistor



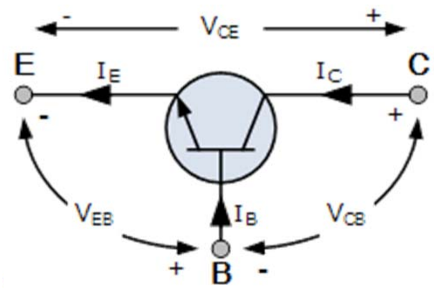
(b) An *pnp* transistor

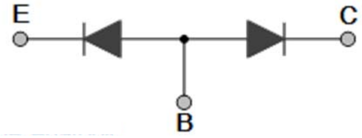


19.3

Bipolar transistor operation

- 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



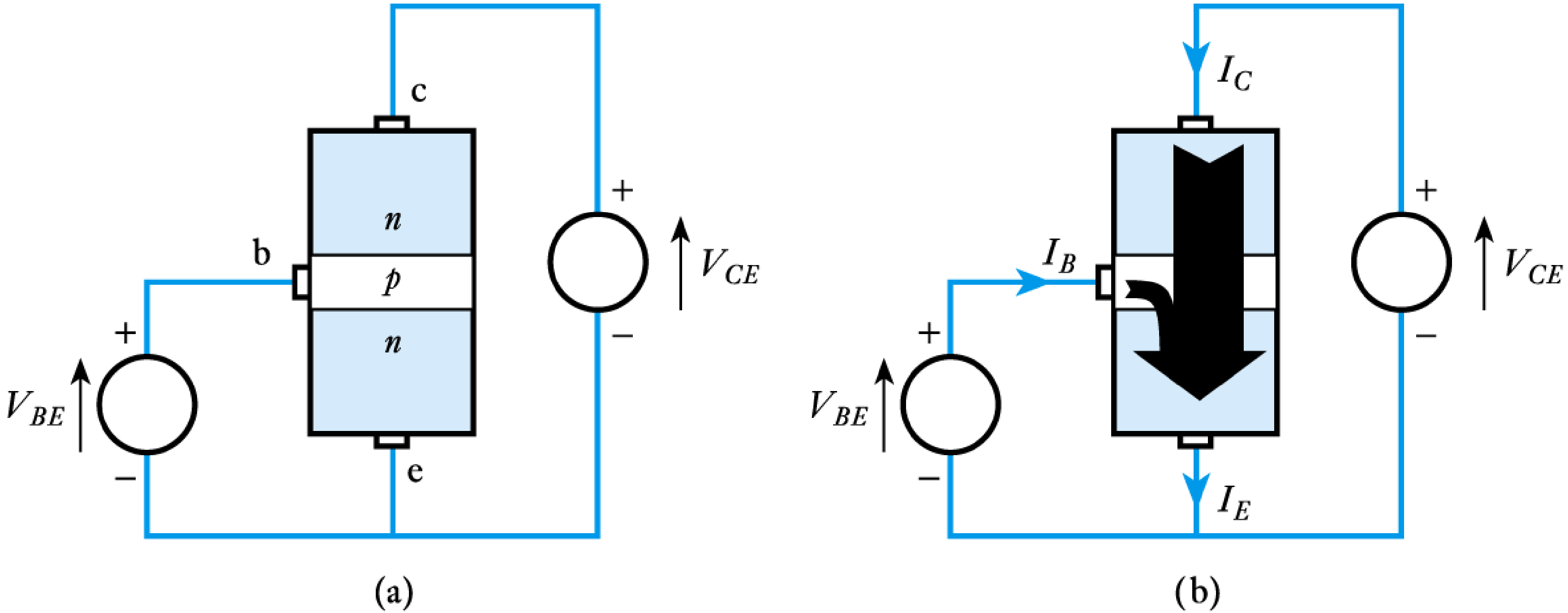


- Now consider what happens when a positive voltage is applied to the base (with respect to the emitter)
  - This forward biases the base-emitter junction
  - The base region is lightly doped and very thin
  - Because it is lightly doped, the current produced is mainly electrons flowing from the emitter 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**

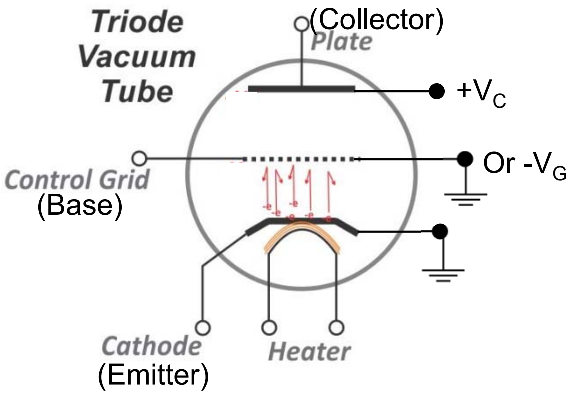
NPN ⇒ **N**ot **P**ointing i**N**

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

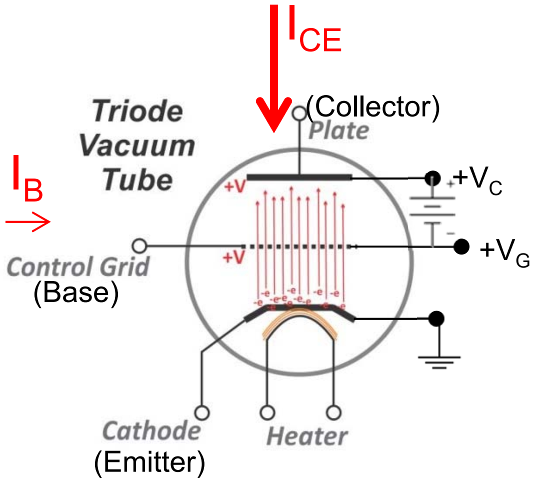
▪ Transistor action



Set the way-back machine, Sherman



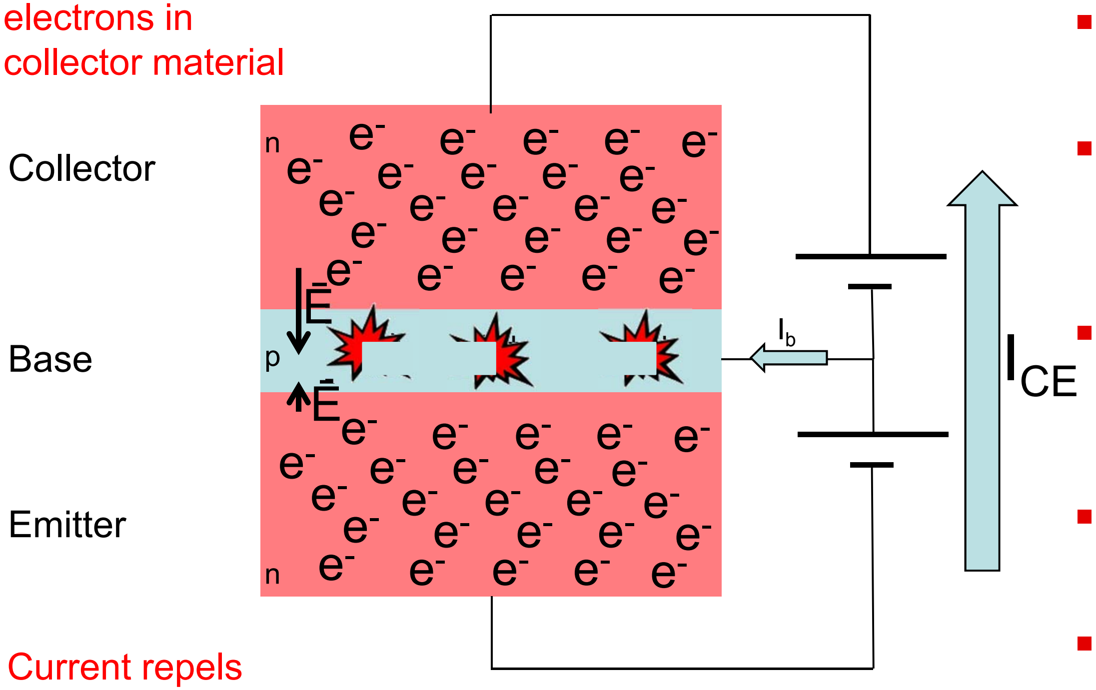
- A NPN transistor!
- Off state,
  - Electrons emitted but shielded from $+V_C$ by grid that is at ground or slightly negative $-V_G$
  - Only a few make it to collector



- 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



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

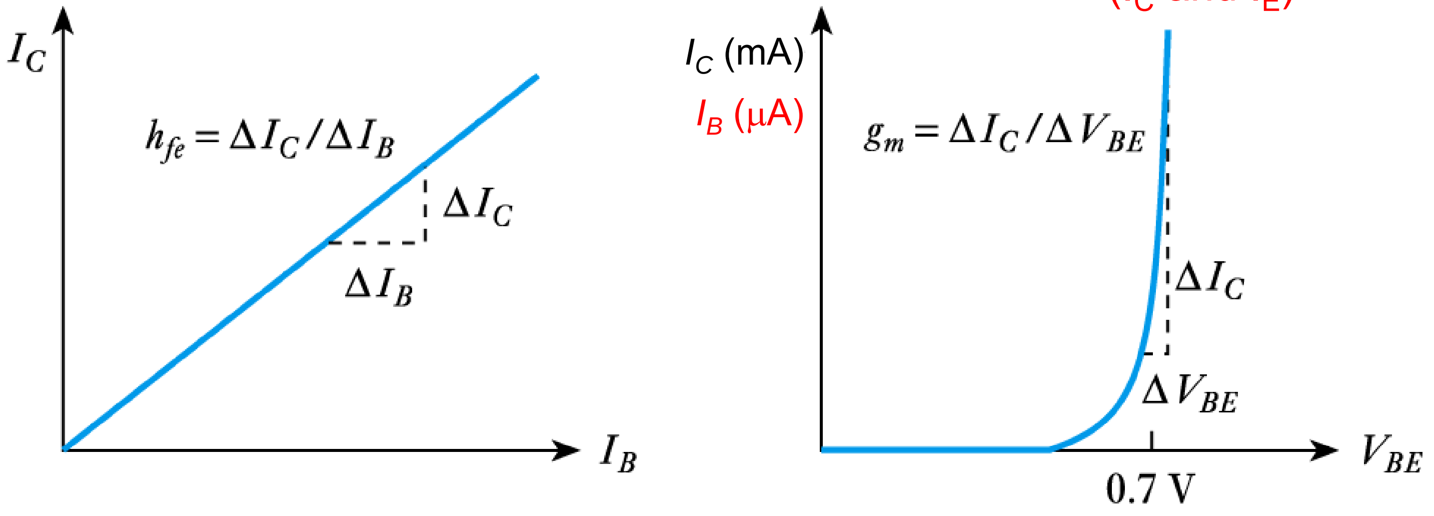
Is it a current or voltage device? Answer: Yes

- 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)

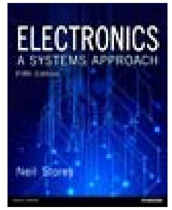


(a) Relationship between output current and input current

(b) Relationship between output current and input voltage

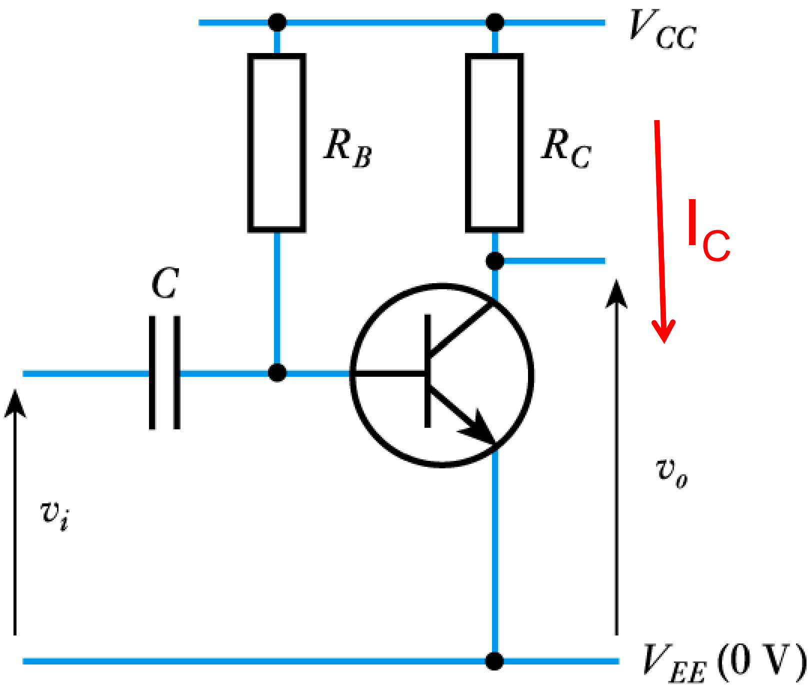
A simple amplifier ($\pm v_i$)

Video 19A

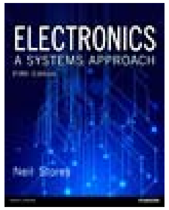


19.4

- 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**



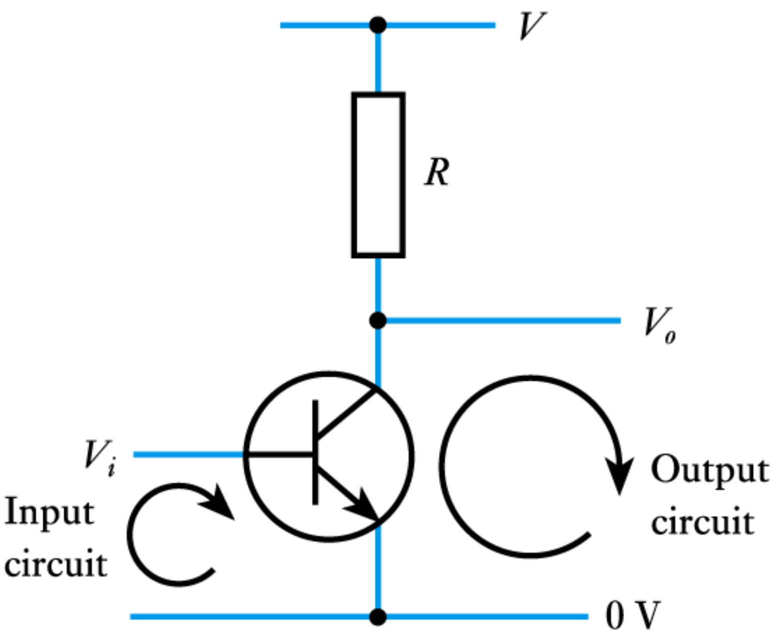
Base more +, increase I_C and more drop across $R_C \Rightarrow v_o$ decreases (inverting)



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

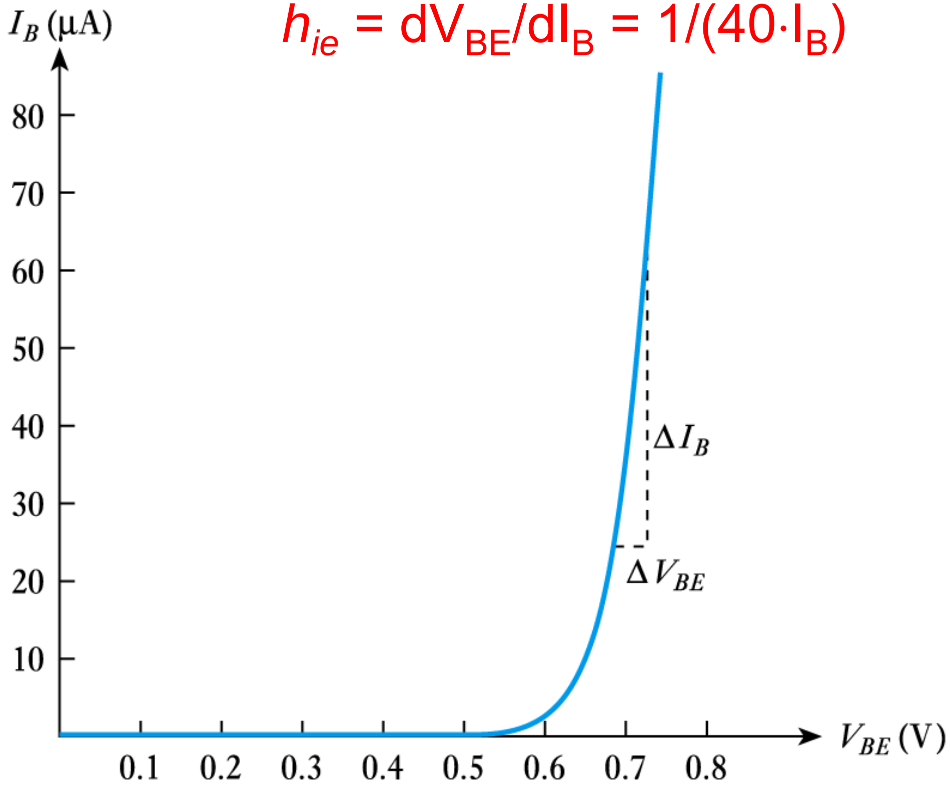


- **Input characteristics**
  - The input takes the form of a forward-biased *pn* junction
  - The input characteristics are therefore similar to those of a semiconductor diode

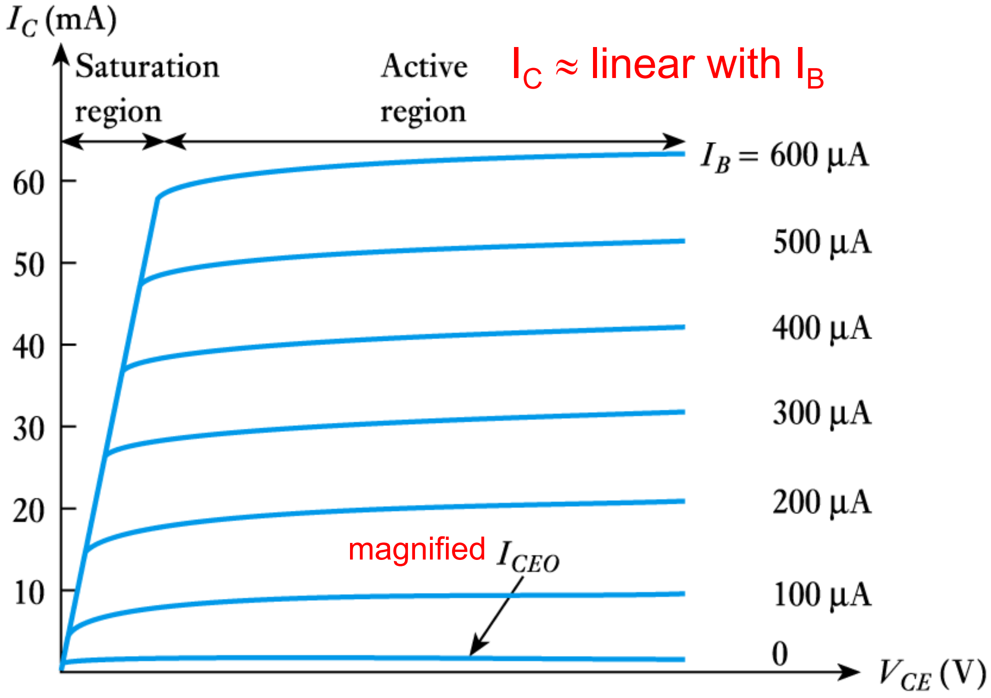
$I_B \approx Constant \cdot e^{40V_{BE}}$

$\therefore$ 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)



- **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

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

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

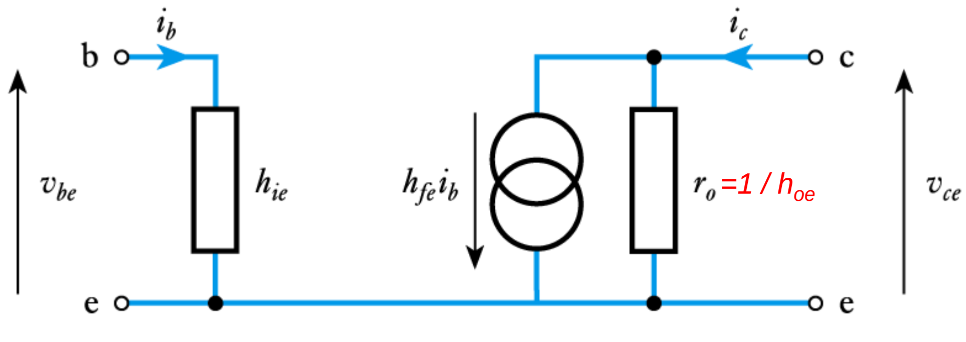
– the units of g_m are those of admittance

– therefore $1/g_m$ has the units of resistance

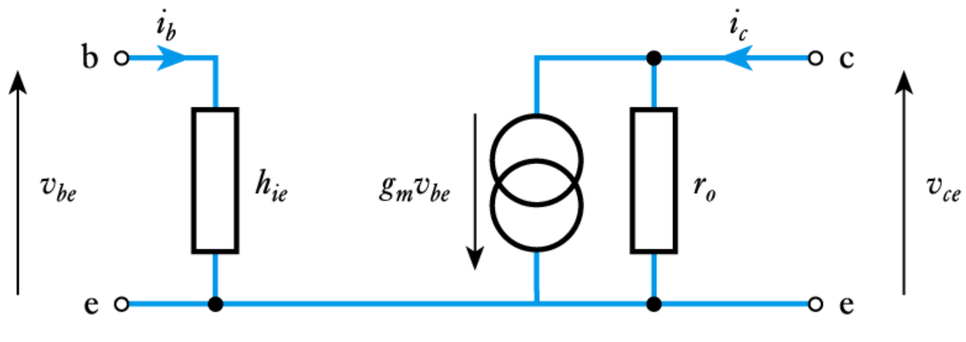
– the quantity $1/g_m$ is termed the **emitter resistance r_e**

– 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**



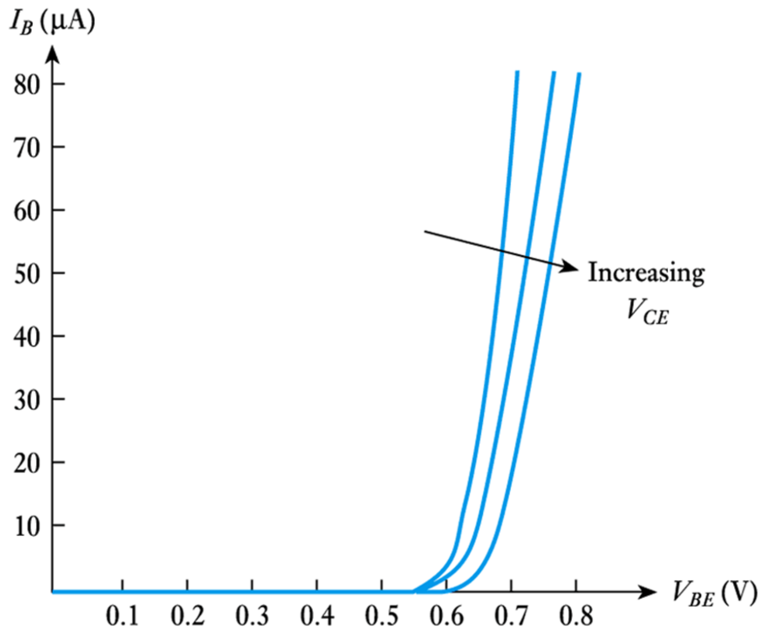
(a)



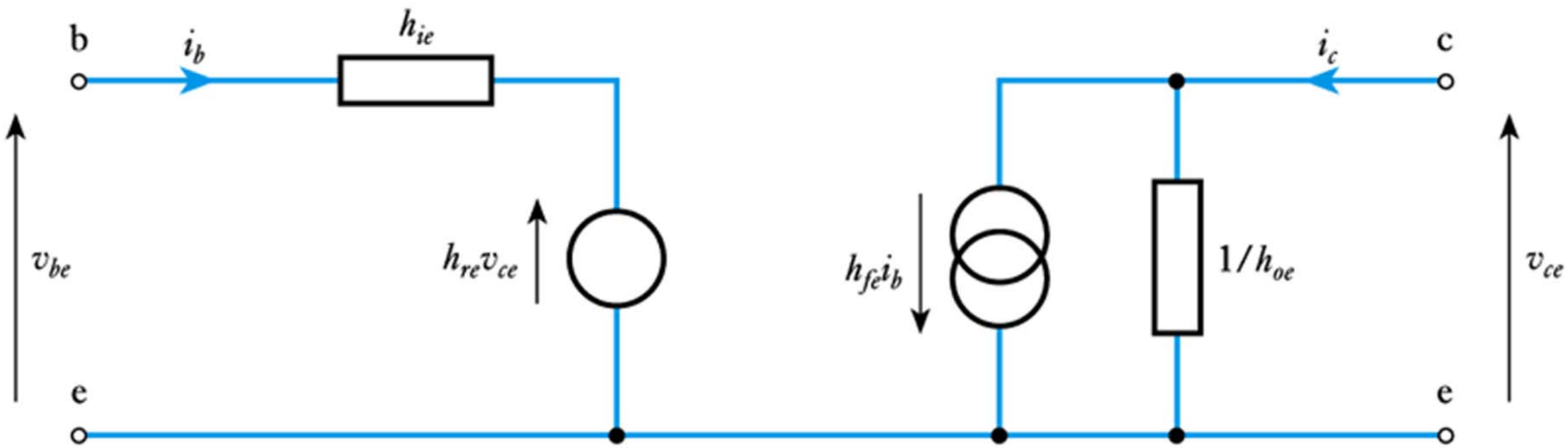
(b)

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

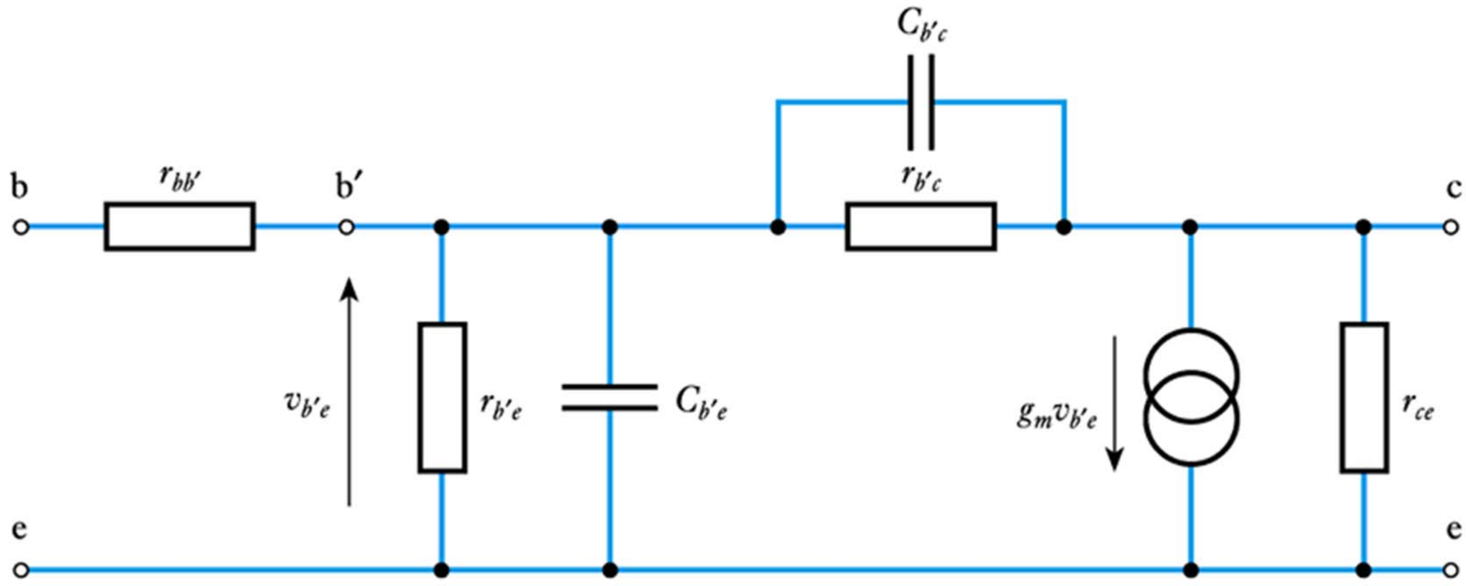
- **Limitations of the simple models**
  - While the simple models shown above give a reasonable representation of the behaviour of devices they do not show the effects of the output voltage on the input (as shown here)
  - This can be modelled by the reverse transfer ratio h_{re}



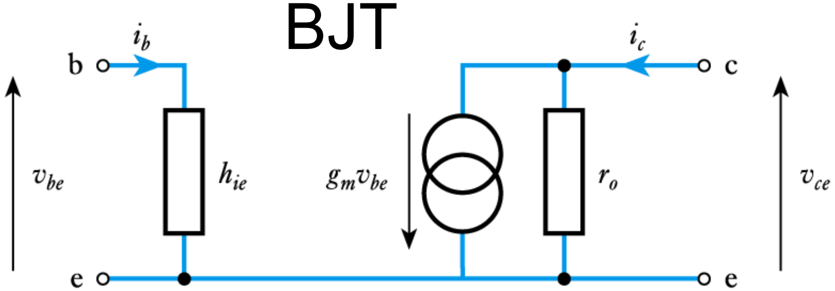
▪ The hybrid-parameter model



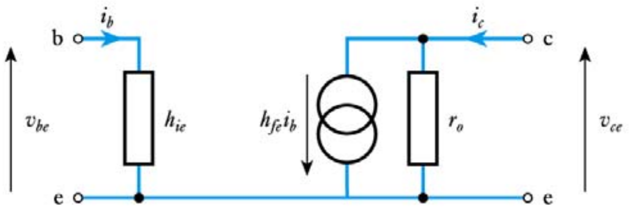
- **The hybrid-π model**
  - gives a better representation at high frequencies



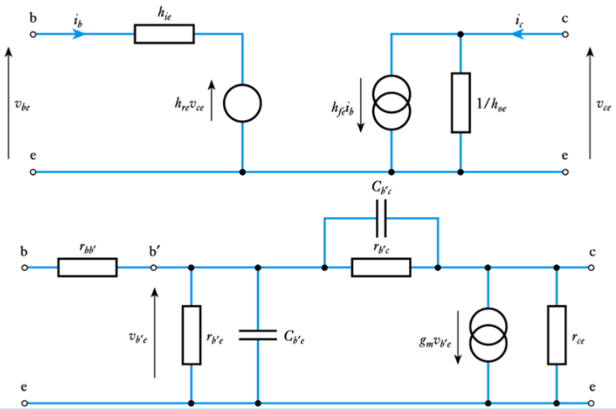
BJT



Simple voltage model

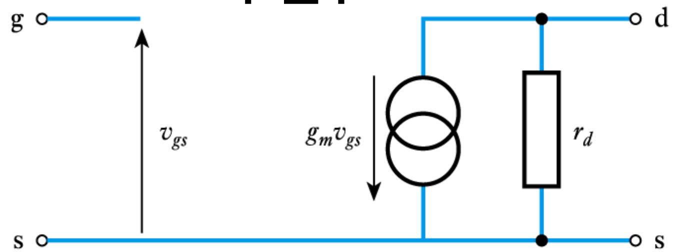


Simple current model



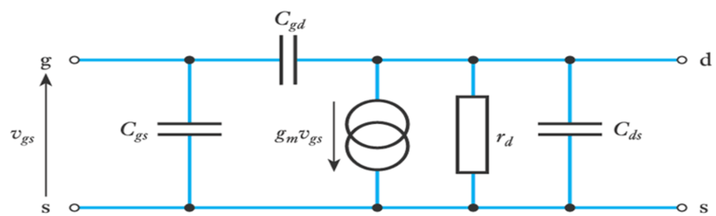
Advanced current models

FET

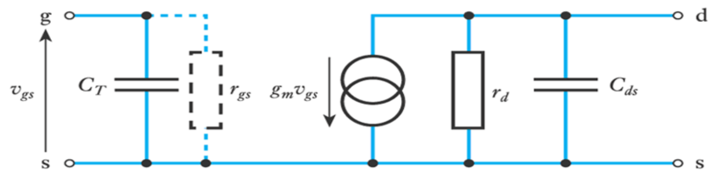


Simple voltage model

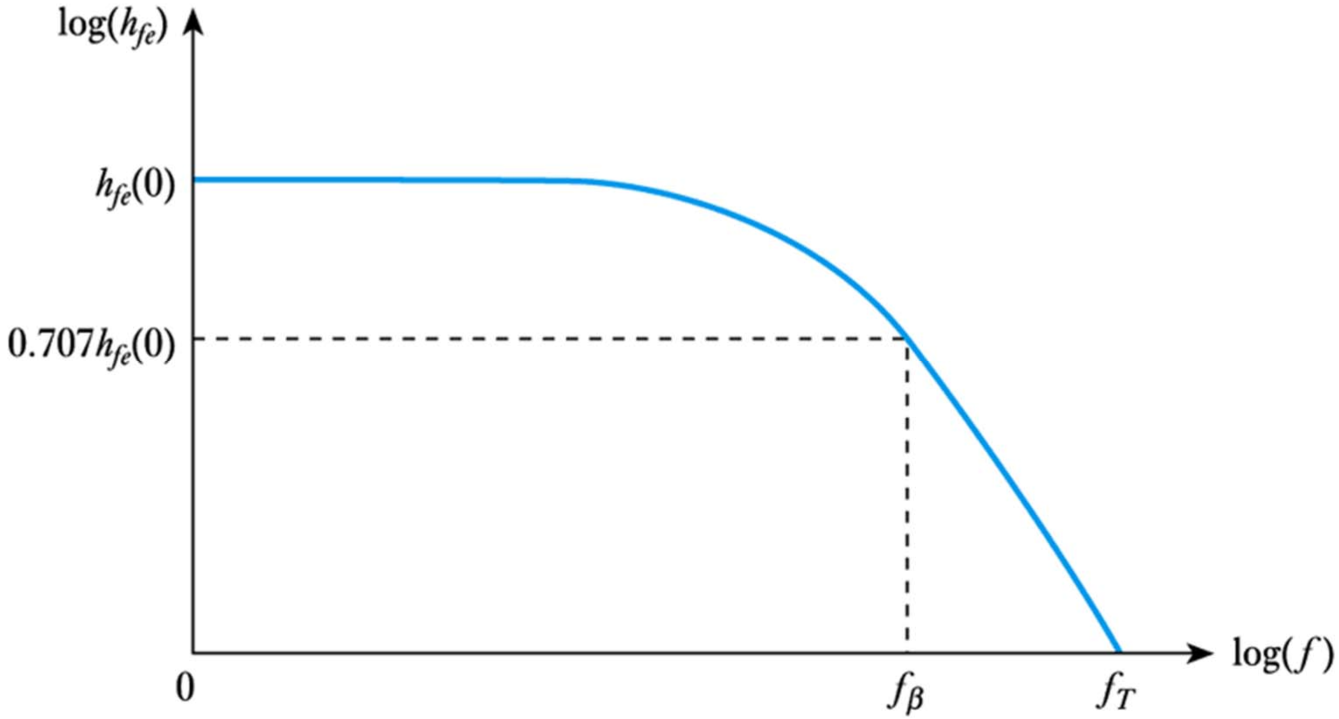
advanced voltage models



(a)



- **Bipolar transistors at high frequencies due to capacitance and resistance between be, bc and ce**



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})	$\Delta V_{CE} / \Delta V_{BE}$	

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

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

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

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

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

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

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

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

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}	C… w…
r_e	E… is, $h_{ie}=h_{fe} \cdot r_e$
h_{re}	E…

$h_{FE} = \ldots$ constant

$I_E = I_C \ldots$

but b… $\cdot\, e^{40 \cdot V_{BE}}$

$I_E \approx h \ldots 0 \cdot I_E$

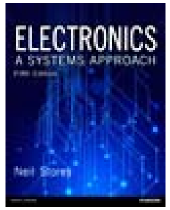
We will only use these to derive results

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 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

Nest 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 transistor applications
- Circuit examples