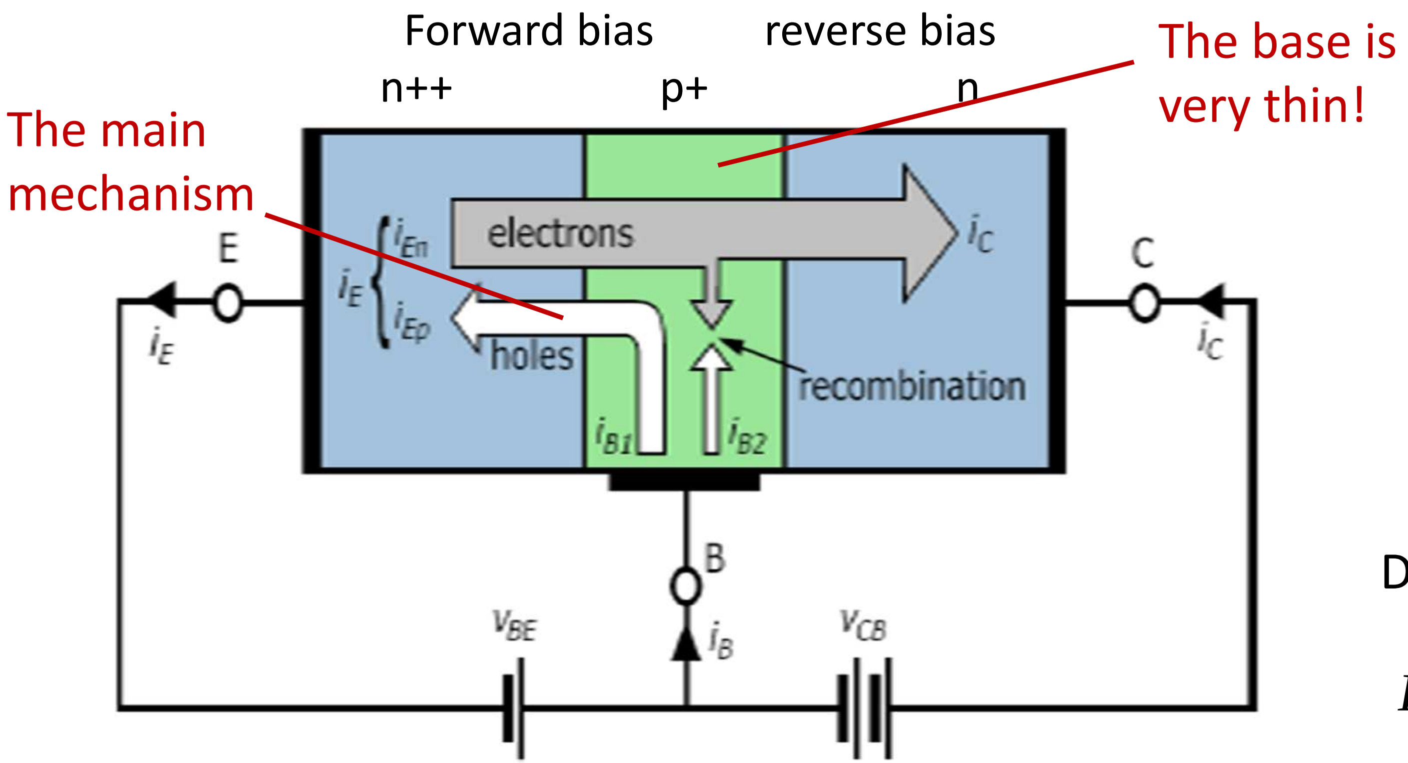
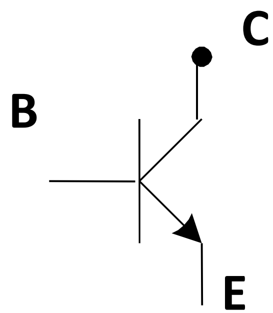
Electronic circuits and systems
ELEC271

Part 1: Transistor models



The bipolar transistor



Device physics gives

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$

Define DC Current Gain

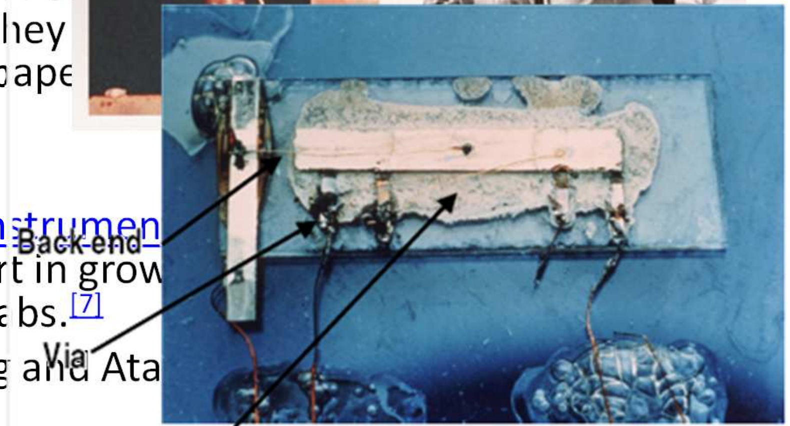
$$h_{FE} = \frac{I_C}{I_B}$$

The history of the transistor

- Physicist Julius Edgar Lilienfeld filed the first patent for a transistor in Canada in 1925, describing a device similar to a field-effect transistor or "FET
- In 1934, German inventor Oskar Heil patented a similar device.[2]

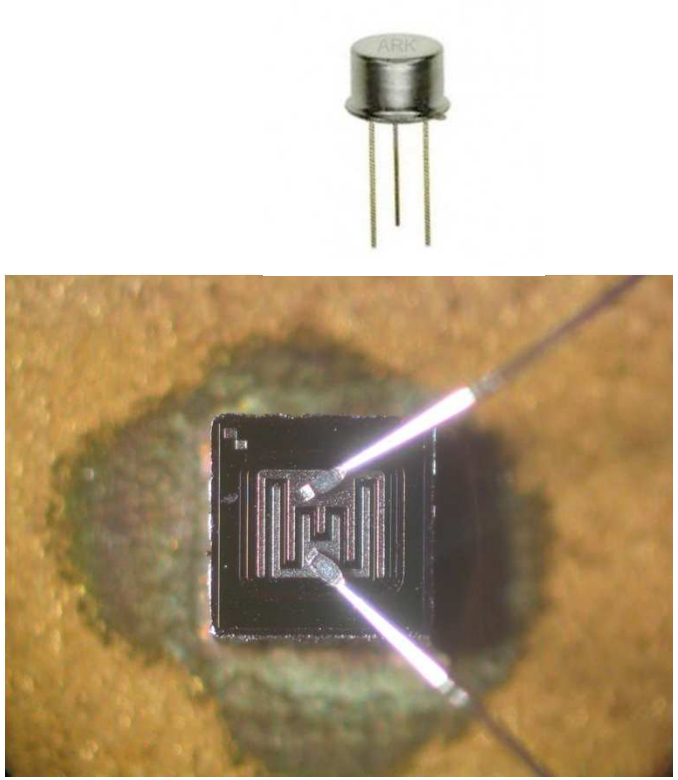
- **In 1947**, John Bardeen and Walter Brattain at AT&T's Bell Labs in the United States observed that when electrical contacts were applied to a crystal of germanium, the output power was larger than the input Solid State Physics Group leader William Shockley saw this, and over the next few months worked to greatly e knowledge of semiconductors. The term *transistor* was R. Pierce as a portmanteau of the term "transfer resist According to physicist/historian Robert Arns, legal pape Labs patent show that William Shockley and Gerald Pe operational versions from Lilienfeld's patents, yet they referenced this work in any of their later research pape articles.[5]

- The first silicon transistor was produced by Texas Instrumen **1954**.[6] This was the work of Gordon Teal, an expert in grow of high purity, who had previously worked at Bell Labs.[7]
- The first MOS transistor actually built was by Kahng and Ata Labs in 1960.[8]

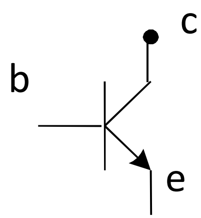


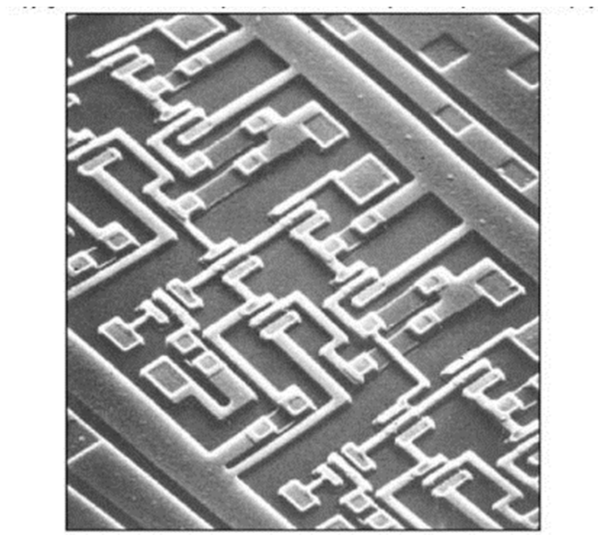
The first IC
Sources: Bell labs and TI

Pictures of bipolar transistors!



A discrete transistor
(1 device in a package)





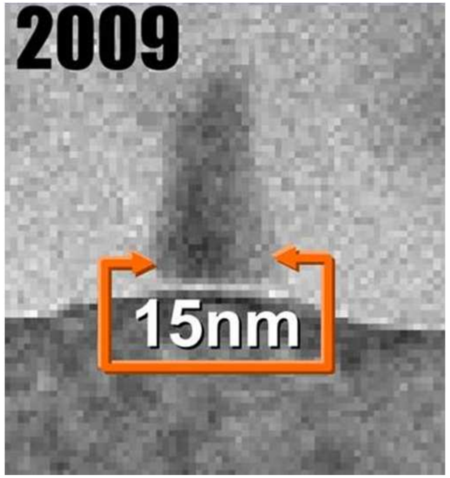
(a)

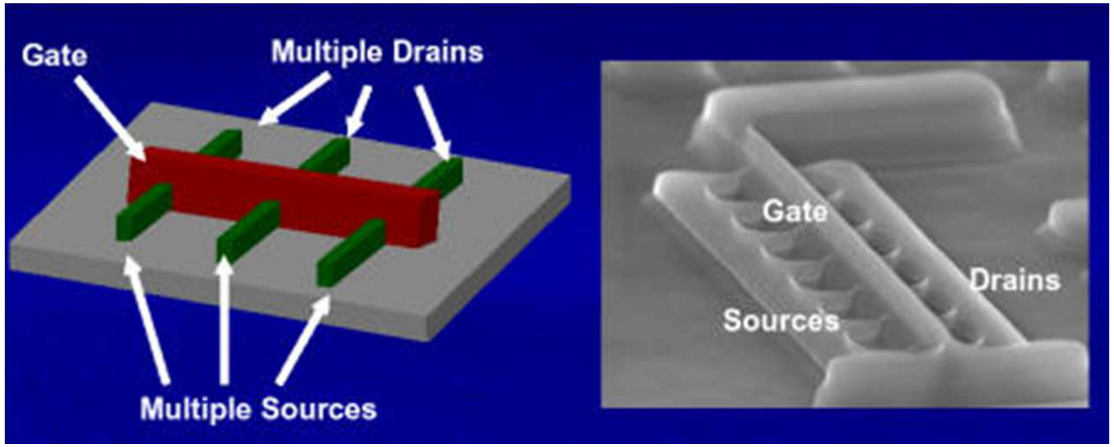
Many transistors **integrated** onto a single piece of silicon semiconductor

Now-a-days...

- How 'big' is an atom?

'FINFETs': Intel 22nm node, 15 nm node





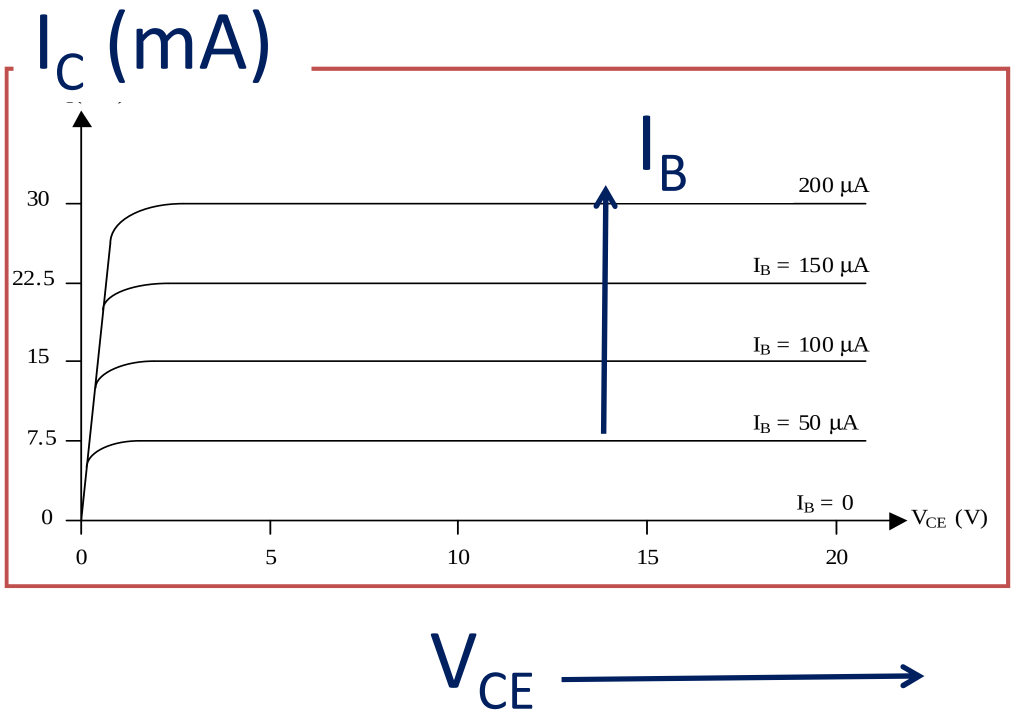
A 'nanometre' is about 1/100,000 the width of a human hair

$1mm = 10^{-3}$ m

$1nm = 10^{-9}$ m

Intel are tooling up for 7 nm node (minimum feature size) production

DC output characteristics



Common-emitter, **DC** current gain

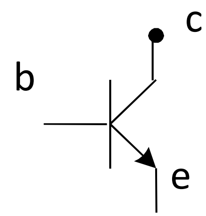
$$h_{FE} = \frac{I_C}{I_B}$$

Common-emitter, **AC** current gain

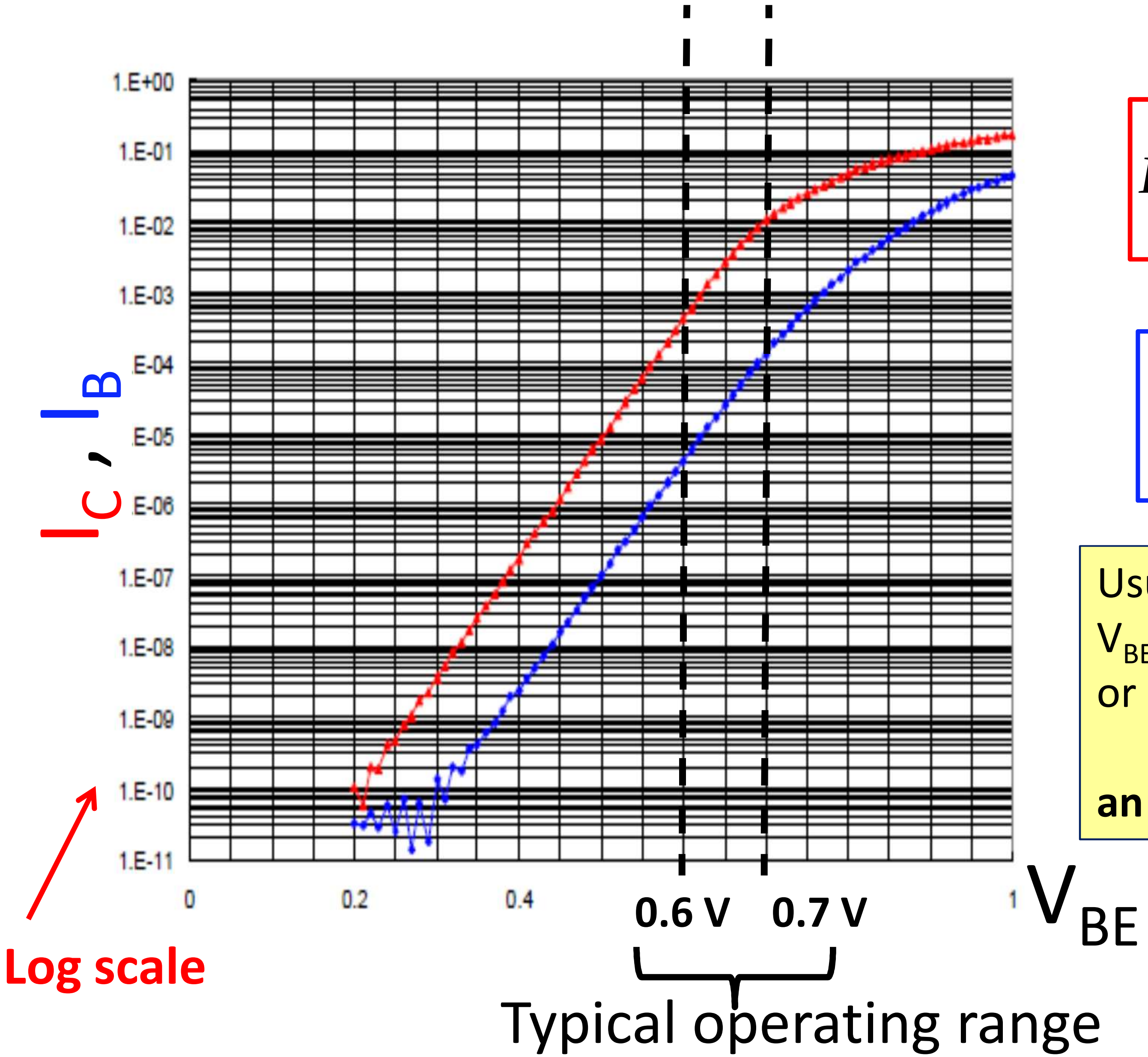
$$h_{fe} = \frac{\Delta I_C}{\Delta I_B} = \frac{i_c}{i_b}$$

Q: How could we estimate AC gain from DC characteristics?

Note: different notation $h_{FE} \equiv \beta$ $h_{fe} \equiv \beta_o$



I_C and I_B versus V_{BE} (transfer characteristics)



$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$

$$I_B = I_{BO} \exp\left(\frac{V_{BE}}{n_B V_T}\right)$$

Usually assume
V_{BE} (on) ~ 0.6 V
or 0. 7 V

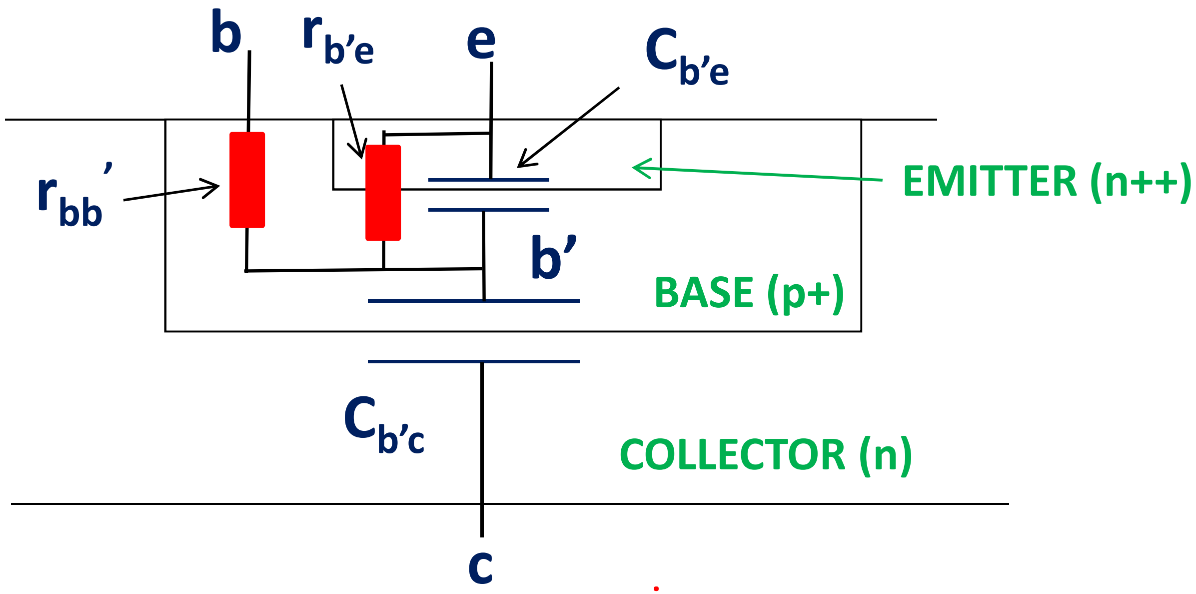
an approximation!

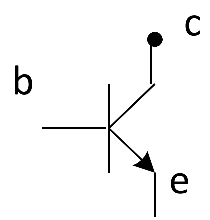
Lawrence Joseph Giacoletto

- Born November 14, 1916, in Clinton, Indiana – October 4, 2004, in Okemos, Michigan)
- an American electrical engineer and inventor. known for his work in the field of semiconductor circuit technology
- in particular the Giacoletto equivalent circuit for transistors
- also known as the hybrid-pi model (1969)

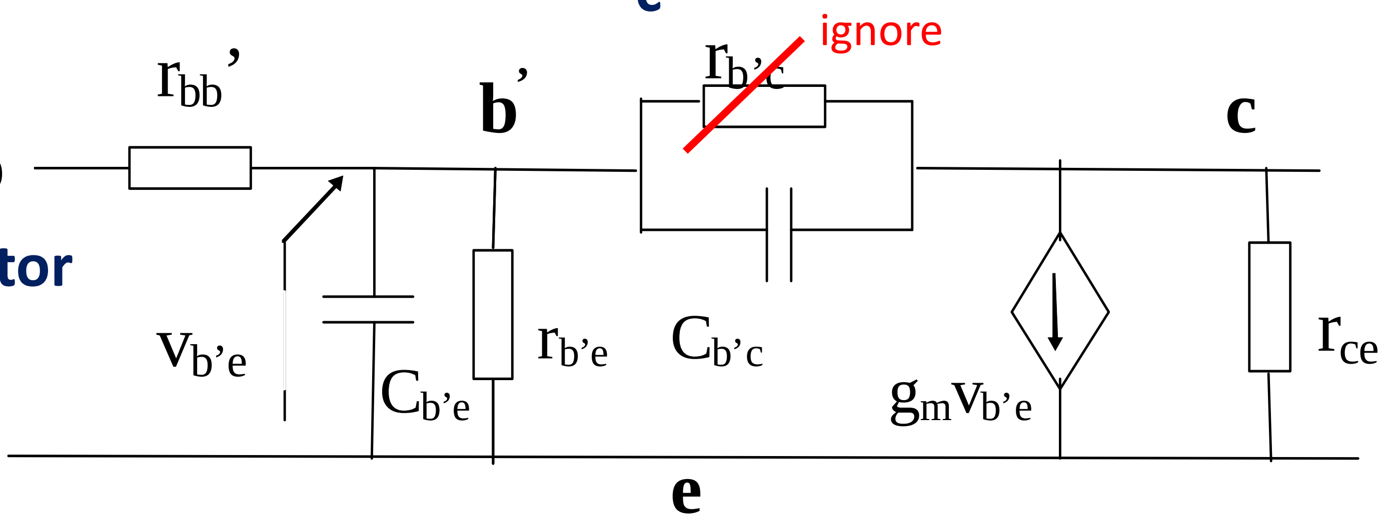
An **ac** equivalent electrical circuit for a transistor: A transistor model known as 'hybrid-pi'

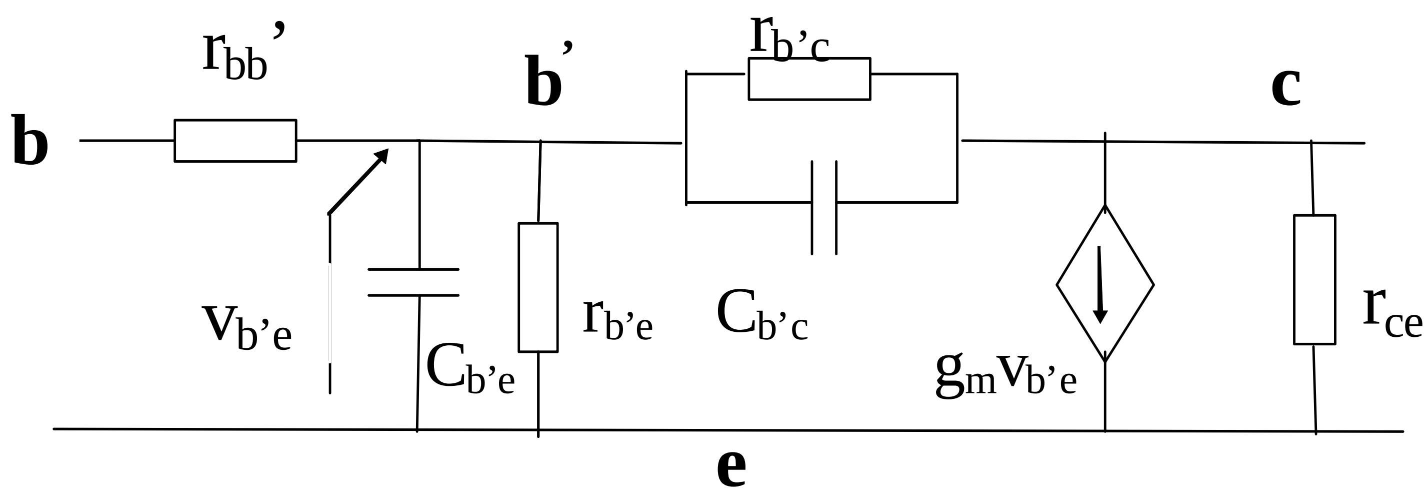
Transistor structure





Transistor model





PARAMETER	PHYSICAL DEFINITION
$r_{bb'}$	*ohmic* resistance of the semiconductor bulk from external base contact to the intrinsic transistor region.
$r_{b'e}$	*dynamic* resistance of the emitter-base junction ($\Delta V_{BE}/\Delta I_B = v_{be}/i_b$)
r_{ce}	*dynamic* resistance of the transistor output characteristic ($\Delta V_{CE}/\Delta I_C = v_{ce}/i_c$)
$r_{b'c}$	Takes care of feedback. Will always be assumed very large and hence ignored.
$C_{b'e}$	differential capacitance of the forward biased emitter-base junction comprising the sum of the depletion and diffusion capacitances. Also written as $\mathbf{C_e}$
$C_{b'c}$	differential capacitance of the reverse biased collector-base junction (capacitance of the depletion region). Also written as $\mathbf{C_C}$
g_m	transistor transconductance ($\Delta I_C/\Delta V_{BE}$ = 40 I_C)

Derivation of parameters from transistor device physics

Recall that the collector current of a bipolar transistor is given by $$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$

where $V_T = kT/q = 25$ mV @ 300K

We can derive other parameters from this equation.

Transconductance

$$g_m = \frac{\Delta I_C}{\Delta V_{BE}} = \frac{I_S}{V_T}\exp\left(\frac{V_{BE}}{V_T}\right) = \frac{I_C}{V_T}$$

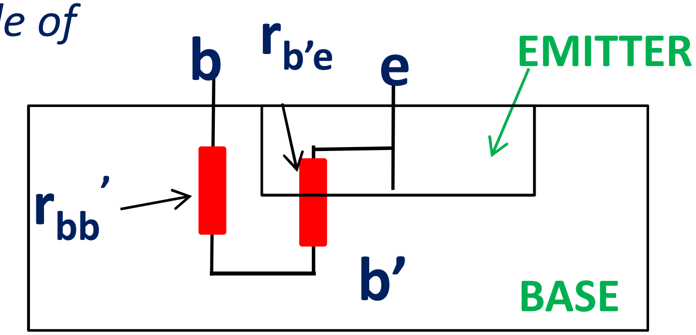
hence **$g_m = 40\ I_C$ Amps/V (IMPORTANT – REMEMBER)**

(N.B $r_e \equiv g_m^{-1}$)

Input dynamic resistance

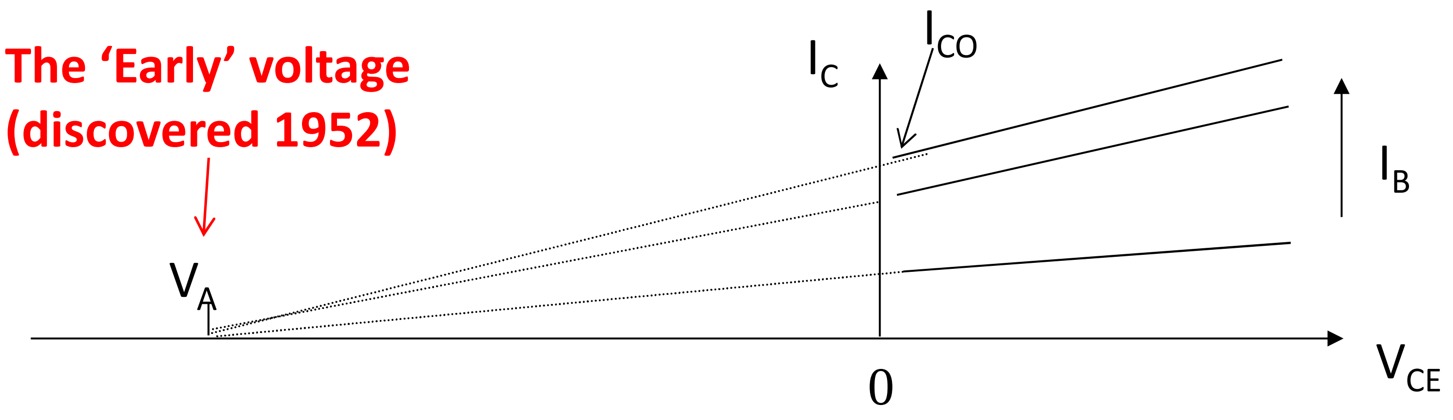
Use the chain rule of differentiation

$$r_{b'e} = \frac{\Delta V_{BE}}{\Delta I_B} = \underbrace{\frac{\Delta V_{BE}}{\Delta I_C}}_{1/g_m}\underbrace{\frac{\Delta I_C}{\Delta I_B}}_{\beta_o} = \frac{\beta_o}{g_m}$$



i.e., **$r_{b'e} = \beta_o/(40\ I_C) = \beta_o/g_m$** **(IMPORTANT – REMEMBER)**

Output dynamic resistance, r_{ce}



JM Early
1925-2004

Can represent the slope on the output characteristic, as: $$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)\underbrace{\left[1+\frac{V_{CE}}{V_A}\right]}_{\text{Models the slope}}$$

Typical values: V_A (npn) ≈ 150 V

V_A (pnp) ≈ 50 V (note that pnp's are generally inferior devices)

Now to find r_{ce}, write Eqn. as $I_C = I_{CO}\left[1+\frac{V_{CE}}{V_A}\right]$

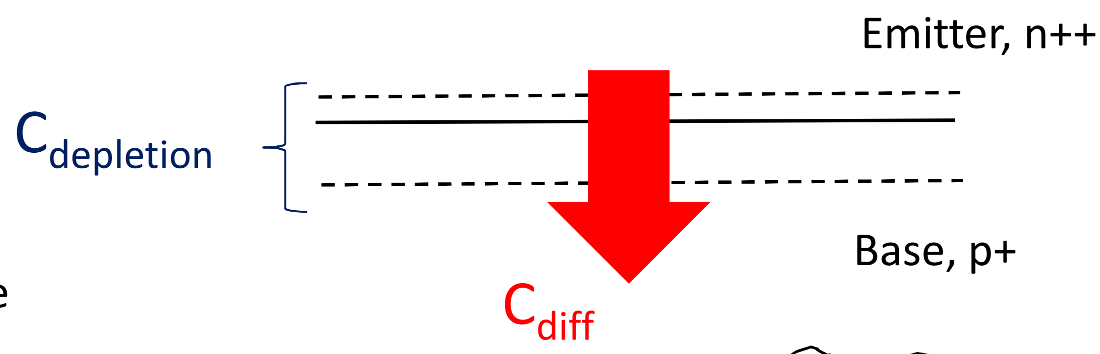
where I_{CO} is the d.c. bias current level of the transistor. Hence $r_{ce} = \frac{\Delta V_{CE}}{\Delta I_C} = \frac{V_A}{I_{CO}}$

or simply write as $r_{ce} = (V_A + V_{CE})/I_C$ with I_C the bias current level.

(note that often, $V_{CE} << V_A$, so we can estimate $\mathbf{r_{ce} \sim V_A / I_C}$) as $V_A >> V_{CE}$

Capacitances

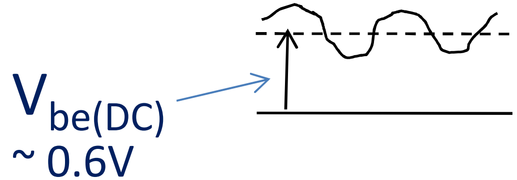
$C_{b'e}$ (or C_e) = $C_{depletion}$ + C_{diff}



$$C_{diff} = \frac{dQ_B}{dV_{BE}}$$

Charge in base varies with ac signal

$$Q_B = I_C \tau_F$$



Where τ_F is an average time for the carriers to pass through the base

$$C_{diff} = \tau_F \frac{dI_C}{dV_{BE}} = \frac{I_C \tau_F}{V_T} \approx C_{b'e}$$

(differentiate $I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$)

Thus C_{be} is not fixed but depends on the bias (collector) current level.

We will show later that :

$$C_{b'c} + C_{b'e} \approx C_{b'e} \approx \frac{g_m}{2\pi \times f_T}$$

f_T is frequency at which the common emitter current gain is unity;

f_T defines the ***bandwidth*** of the transistor and will be investigated later in the course.

Example

Q: Sketch the small-signal equivalent circuit for an npn bipolar transistor.

determine values for the small signal parameters r_{be}, g_m and r_{ce} when the transistor is operating at a quiescent DC collector current I_{CQ} = 2mA and collector-emitter voltage V_{CE} of 10V.

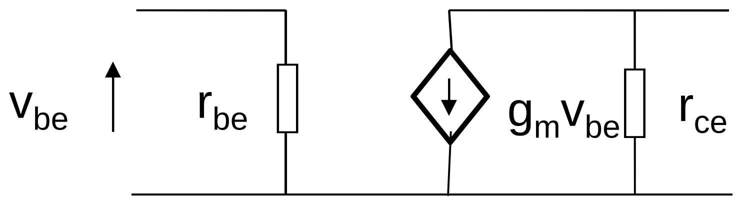
[β_o =100 and V_A = 150V]

Note units!

$$g_m = 40 I_C = 40 \times 2\text{mA} = 80\ \text{mA/V}$$

$$r_{be} = \frac{\beta_o}{g_m} = \frac{100}{80 \times 10^{-3}} = 1.25\ \text{k}\Omega$$

$$r_{ce} = \frac{(10+150)}{2 \times 10^{-3}} = 80\ \text{k}\Omega$$



Calculate the values of I_C, I_E and I_B of a transistor in the common emitter configuration, when V_{CE} = 8V and V_{BE} =0.63V; given that $I_S = 10^{-13}$ A at V_{CE} = 5V, β = 200 and V_A = 150V.

Solution $$I_C = I_{CO}\left[1+\frac{V_{CE}}{V_A}\right]$$ Where $$I_{CO} = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$

so when V_{BE} = 0.63V, I_S = 10^{-13} A; **I_{CO} ~ 9mA**

$$I_C = 9mA\left[1+\frac{5}{150}\right]$$

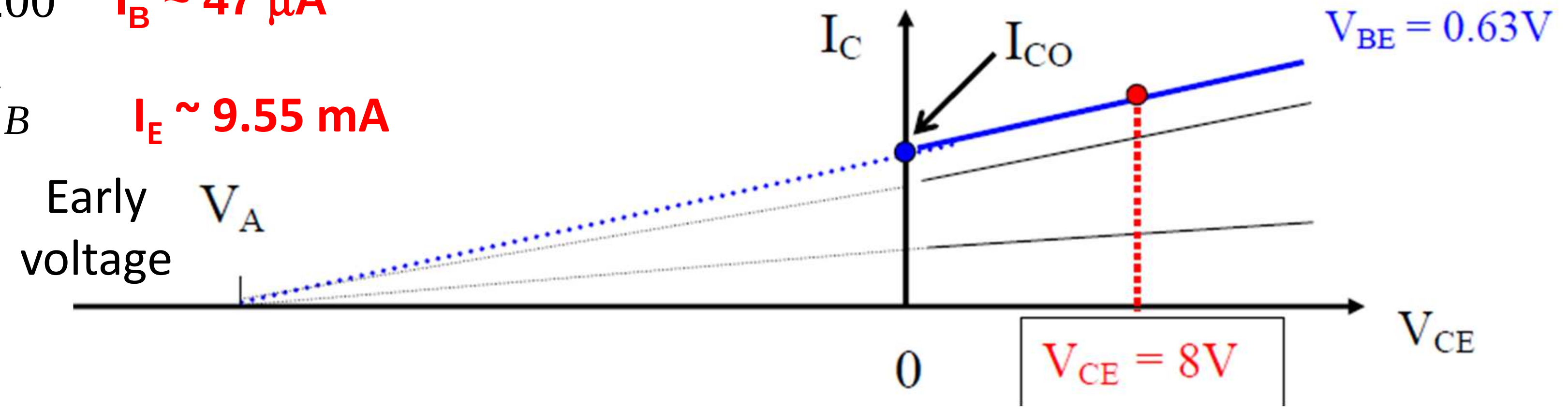
I_C at V_{CE} = 5V is 9.3mA

We need to find I_C, I_B and I_E at V_{CE} = 8V

Therefore $$I_C = 9mA\left[1+\frac{8}{150}\right]$$ **~ 9.5 mA**

$$\beta = \frac{I_C}{I_B} = 200$$ **I_B ~ 47 μA**

$$I_E = I_C + I_B$$ **I_E ~ 9.55 mA**



What is the output resistance of the transistor at the operating point?

Operating point is $V_{CE} = 8V$, $I_C = 9.3mA$

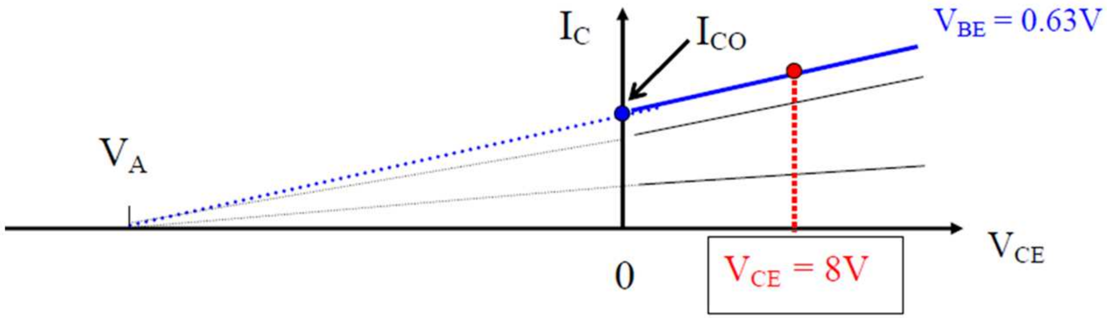
So
$$r_{ce} = \frac{V_A + V_{CE}}{I_C}$$

$$r_{ce} = \frac{150+8}{9.3 \cdot 10^{-3}} = 17\ k\Omega$$

or

$$r_{ce} = \frac{V_A}{I_{CO}}$$

$$r_{ce} = \frac{150}{9 \cdot 10^{-3}} = 17\ k\Omega$$



MCQ

The input side of a small signal equivalent circuit contains resistances rbb’ and rb’e . How would you describe these two elements.

a) Essentially the same thing

b) Both depend on the DC bias conditions (at low current levels)

c) They both depend on the AC conditions

d) rbe’ depends on the DC bias conditions and rbb’ doesn’t (at low currents)

MCQ: Answer

The input side of a small signal equivalent circuit contains resistances rbb’ and rb’e . How would you describe these two elements.

a) Essentially the same thing

b) Both depend on the DC bias conditions (at low current levels)

c) They both depend on the AC conditions

d) rbe’ depends on the DC bias conditions and rbb’ doesn’t (at low currents)

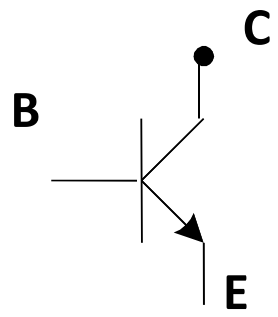
Exercises

1. Calculate g_m, r_e and r_{be} when I_C = 10 μA and when I_C = 0.25mA.
   Comment on the values (β_o = 200)
2. Why is the small-signal equivalent circuit of a battery (d.c. voltage source) taken to be a short circuit?
3. What would be the small signal equivalent circuit of an ideal current source?
4. What are the equivalent circuit parameters for a transistor whose β_o = 200 and whose Early voltage is 150V when it is operating at I_C = 0.1mA and V_{CE} = 5V?
5. Calculate the values of I_C, I_E and I_B of a transistor in the common emitter configuration, when V_{CE} = 8V and V_{BE} =0.63V;
   given that $I_S = 10^{-13}$ A at V_{CE} = 5V, β = 200 and VA = 150V.
6. What is the output resistance of the transistor at the operating point in 5 above?

Part 2: Bipolar transistor amplifier configurations

• established an ac model for the bipolar transistor,
• now analyse the basic amplifier configurations.

1. **Common emitter (CE)**
2. **Common emitter with emitter degradation (CE-ED)**
3. **Common collector (CC) also known as emitter follower (EF)**
4. **Common base (CB)**



• voltage and current gains, input and output resistance etc.
• each configuration has particular properties that we can usefully employ when building up complex electronic circuits....

.. by cascading stages!

So look at examples of two and three stage amplifiers

Golden Rules for drawing equivalent circuits

1. Draw the equivalent circuit of the transistor first
2. Identify the a.c. grounds (voltage sources look like short circuits for a.c. currents!)
3. Convert capacitors to short circuits (we are interested in 'mid-frequency' regimes where the impedance of coupling/de-coupling capacitors is zero
4. Add the other circuit components (resistors)to obtain the complete equivalent circuit.