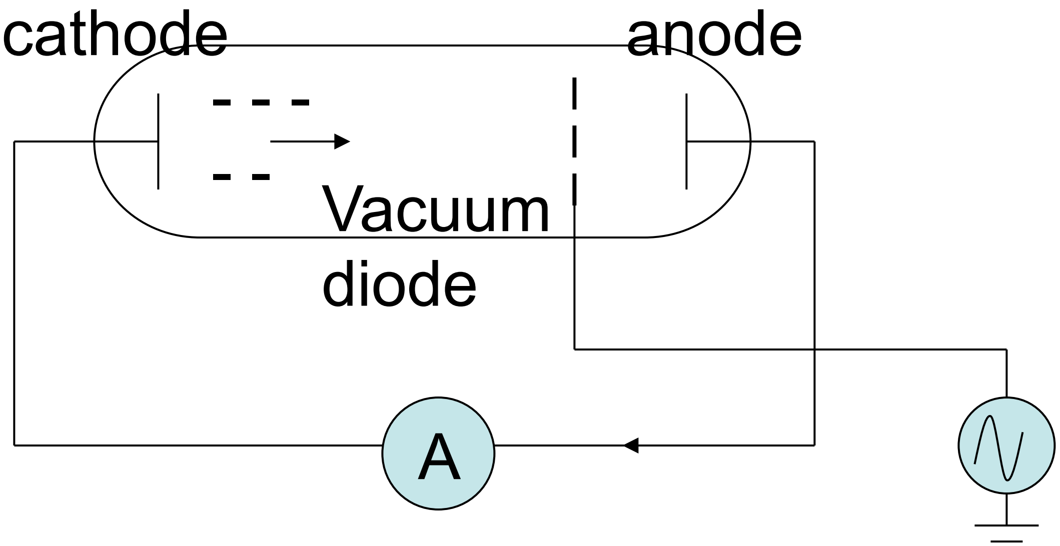
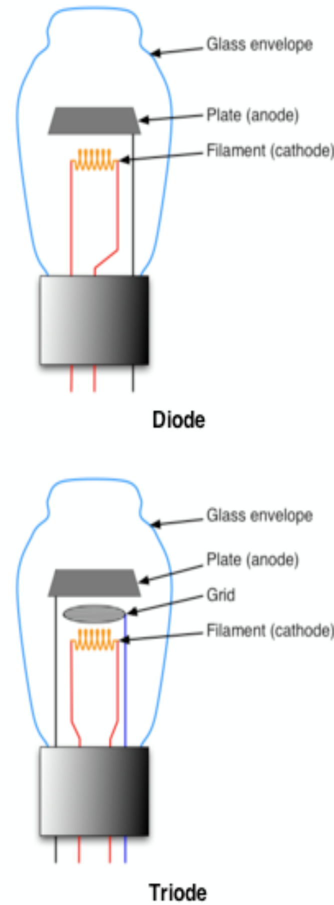
Vacuum Tube





- Evacuated tubes used in PhotoElectric Effect and early X-ray work circa 1890.

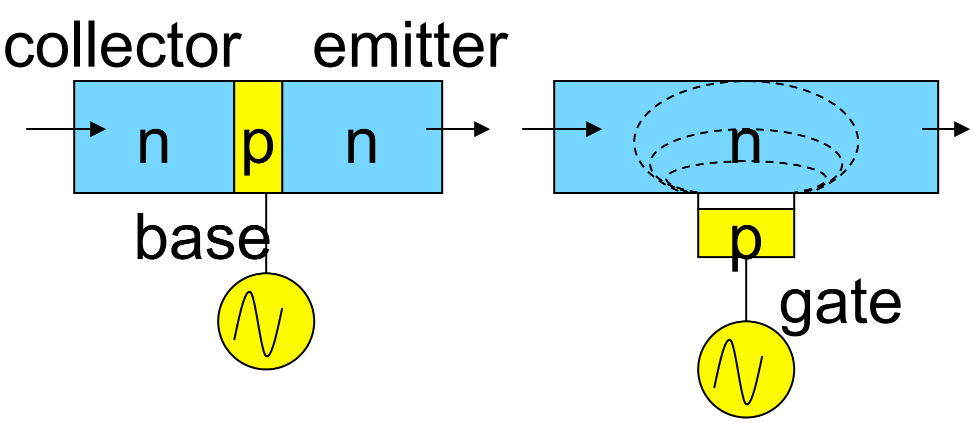
- Vacuum tube invented circa 1903 for radio by Marconi group. Diode action!

- Triode allowed modulation of anode current by small change in grid voltage.

Solid State Transistors

-Lilienfeld, Heil (Germany)
-Shockley and Pearson
(Bell Labs Patent) circa 1930.
- Current modulation and gain

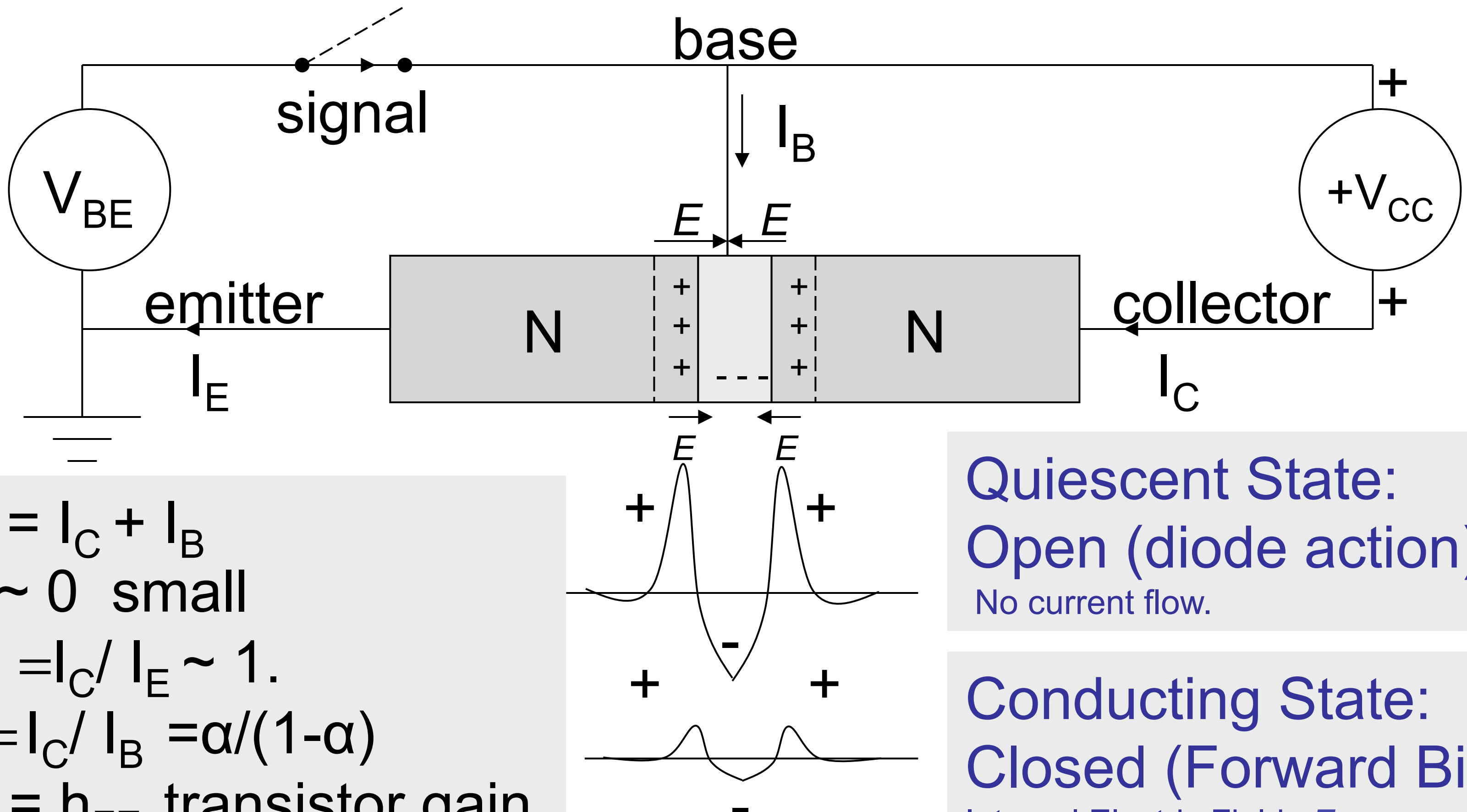
$$I_{CE} = \beta\, i_{BE} \quad (\beta \approx 100)$$



bipolar   field effect

Assorted discrete transistors

BiPolar Transistor Operation



$I_E = I_C + I_B$
$I_B \sim 0$ small
$\alpha = I_C / I_E \sim 1.$
$\beta = I_C / I_B = \alpha/(1-\alpha)$
$B = h_{FE}$ transistor gain

Quiescent State:
Open (diode action)
No current flow.

Conducting State:
Closed (Forward Bias)
Internal Electric Fields *E* are cancelled.

Holes injected into base lower barrier potential.
V_{CE}>2V to allow electrons to flow across barrier .

(They can be captured by injected holes!)

Cross Section of an NPN Bipolar Device

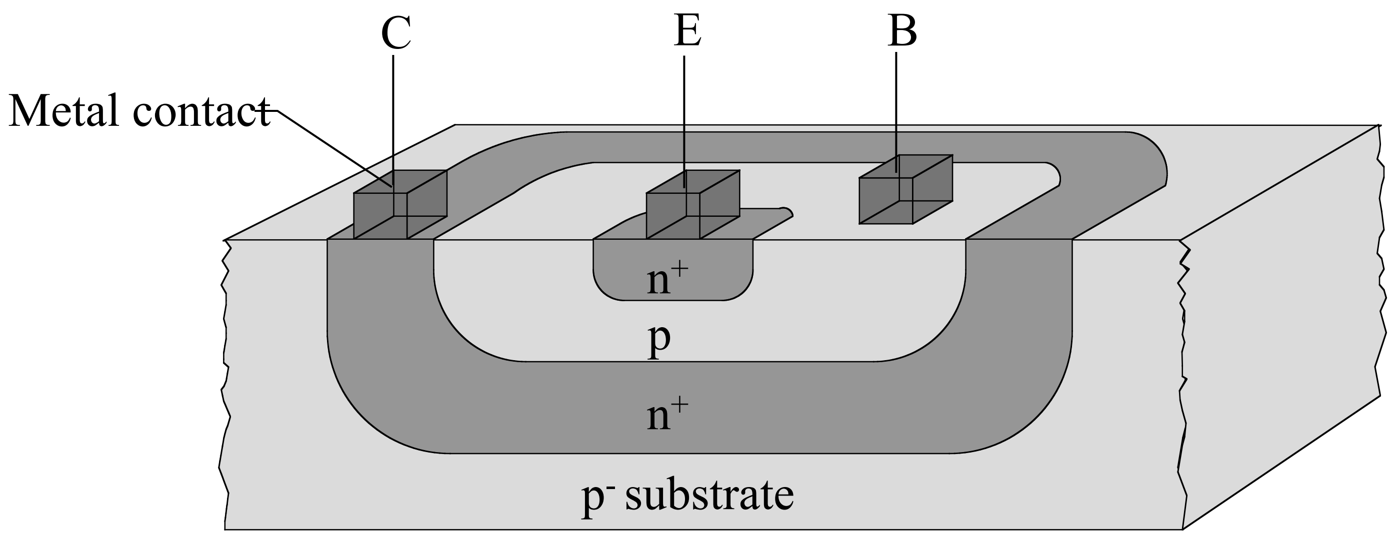
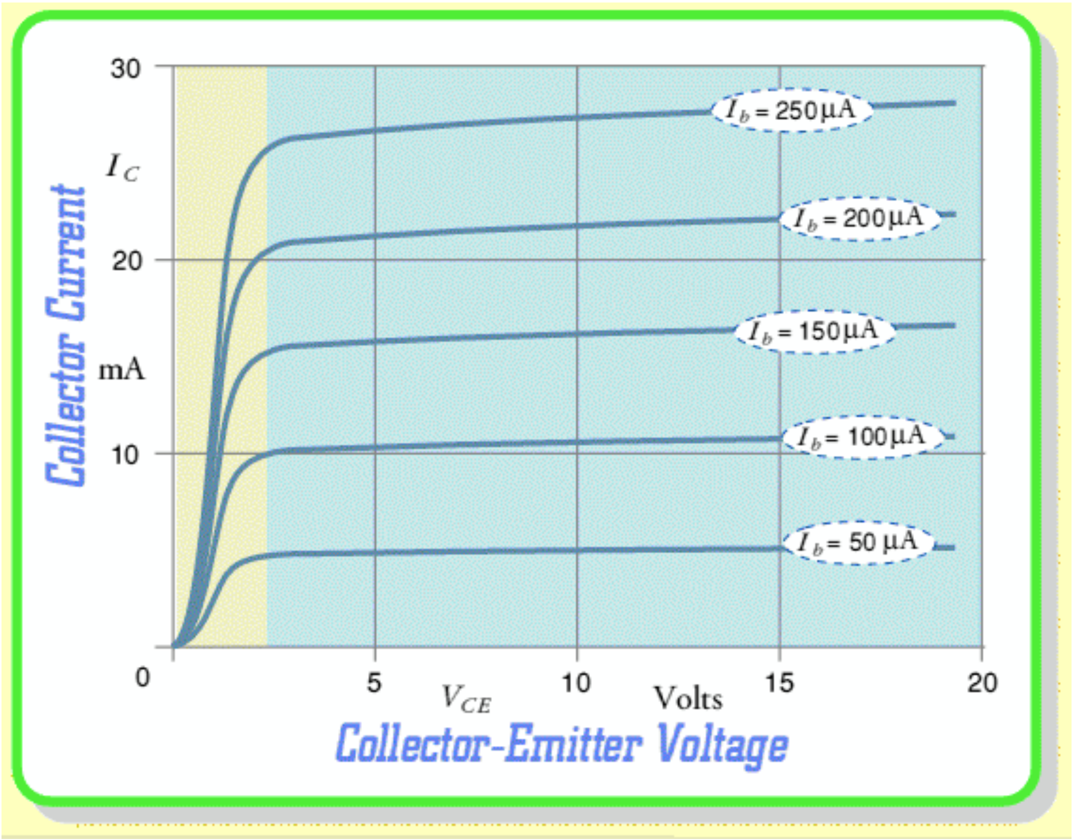


Figure 3.13

Transistor Curves

•I_C the current through the collector is almost constant when the transistor is operated in its linear range. $I_C = \beta I_B$

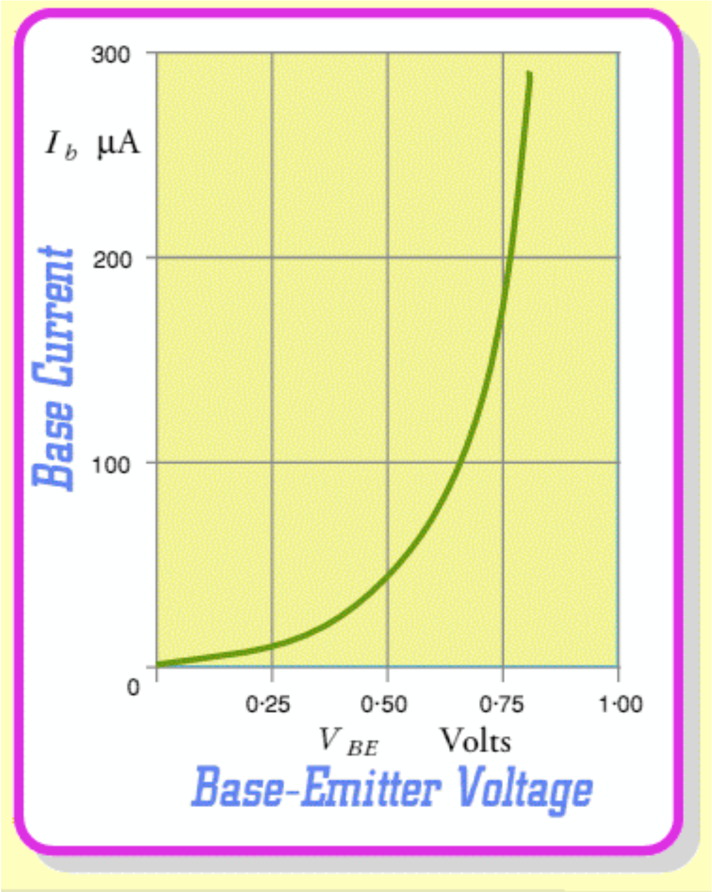


http://www.st-andrews.ac.uk/~jcgl/Scots_Guide/info/comp/active/BiPolar/bpcur.html

Transistor Curves

- The base current I_B will begin to flow freely when V_{BE}>0.7V .
- We say the transistor has turned on at this point.

$I_C = \beta I_B$



http://www.st-andrews.ac.uk/~jcgl/Scots_Guide/info/comp/active/BiPolar/bpcur.html

Amplification and Zin

Amplification

1) $I_E = I_b + I_C \quad \rightarrow \quad \delta I_E = \delta I_C$

2) $\beta = I_C / I_b \sim I_E / I_b \quad (I_b \sim 0 = few\ \mu A)$

2) $V_E = V_b + 0.7V \quad \rightarrow \quad \delta V_b = \delta V_E = \delta I_E R_E$

2) $V_{CC} = V_C + V_E + 0.7V \quad \rightarrow \quad \delta V_E = -\delta V_C = \delta I_C R_C$

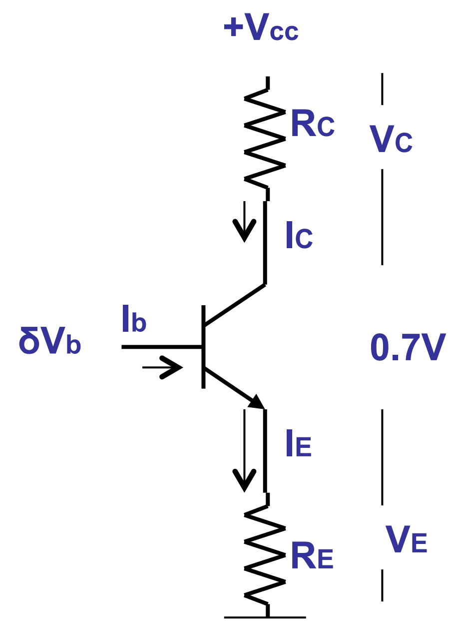
$$A_V = \frac{\delta V_C}{\delta V_b} = \frac{-\delta I_C R_C}{\delta I_E R_E} = -\frac{\delta I_C R_C}{\delta I_C R_E} = -\frac{R_C}{R_E}$$

$$\boxed{A_V = -R_C / R_E}$$

Input Impedance (Im *pedance looking in to base*)

$$Z_{IN} = V_b / I_b \approx V_E / I_b = I_E R_E / I_b = \left(I_E / I_b\right) R_E = \beta R_E$$

$$\boxed{Z_{IN} = \beta R_E}$$



Temperature Dependence

The base-emitter voltage of the silicon pn junction in a transistor is written as a function of temperature T, reference temp T_0, bandgap gap voltage Vg, collector current I_C and current I_{C0} at T_0.

$$I_C = I_{C0} \; e^{\frac{qVg}{kT}(1-T/T_0)+\frac{qV_{BE0}}{kT}(T/T_0)} \times \; e^{\frac{qV_{BE}}{kT}}$$

This temperature dependence will make any transistor amplifier gain drift up or down. Differential pairs of transistors are commonly used to cancel ***common mode*** *drifts.*

$$I_C \sim I_{C0} \; e^{\frac{qV_{BE}}{kT}}$$

Differential Pair

- In order to cancel transistor temperature drifts and some *common mode noise* we commonly see a differential pair used.
- Temperature dependent leakage currents in the two transistors tend to cancel when Q1 and Q2 are located near each other.
- When the input is grounded Q1 and Q2 cancel each others signal so the output is clamped to zero also.

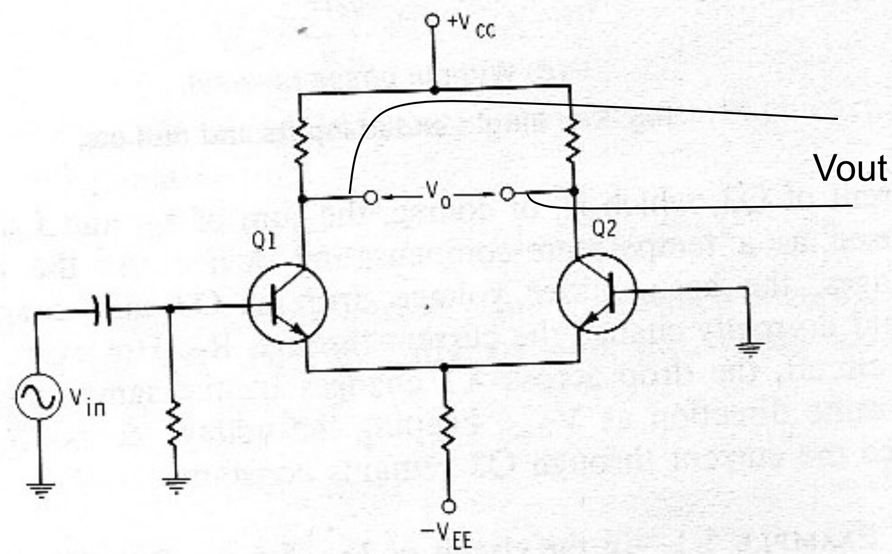
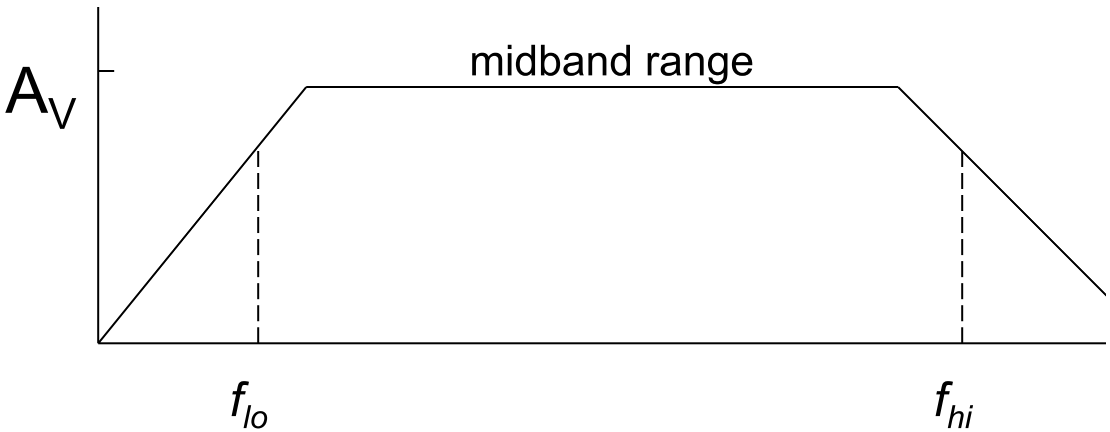
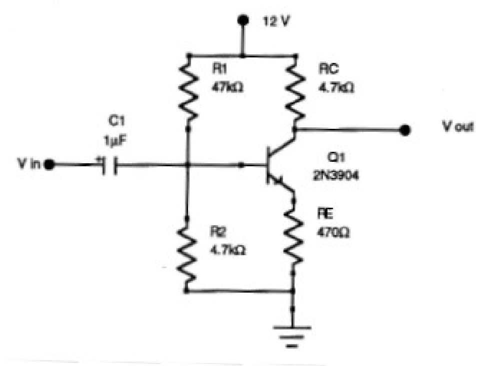


Fig. 5-3. Amplifier with single-ended input.

Frequency Response

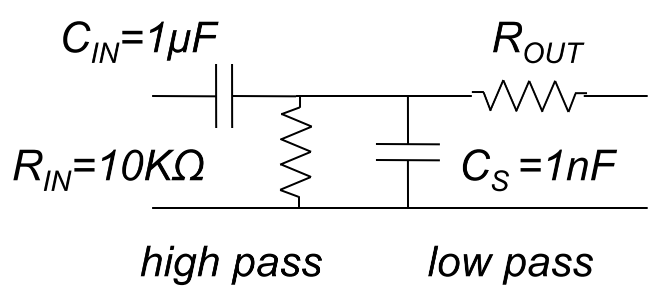




- We can think of the amplifier as a combination of low and high pass filters in the circuit below.
- f_{lo} = mainly due to the input capacitor C_{IN} and input impedance $R_{IN}=Z_{IN}$.
- f_{hi} = The stray capacitances C_S is internal to the every circuit and represents small capacitances due to connection leads and internal fabrication. $R_{OUT}=Z_{OUT}$

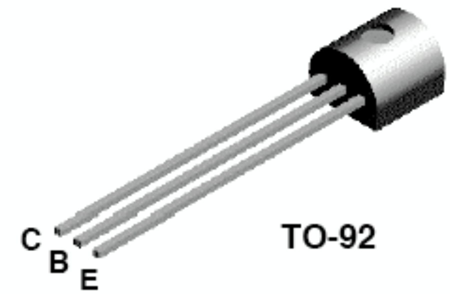
$$f_{lo} \sim \frac{1}{2\pi R_{IN} C_{IN}}$$

$$f_{hi} \sim \frac{1}{2\pi \mathrm{R}_{OUT} C_S}$$



Common Emitter Amplifier

2N3904



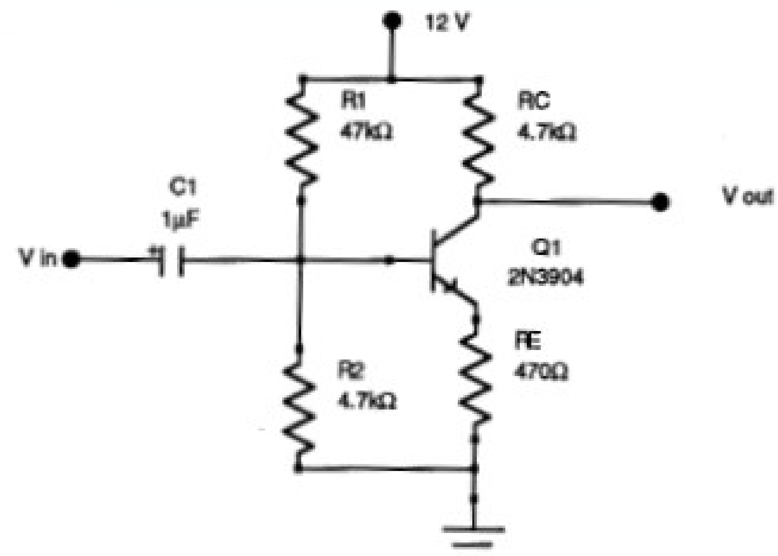
- Emitter is grounded ➔ " Common Emitter "
(Signal Source and load share the ground at E)

- NPN Transistor with positive +Vcc forward biases the base-emitter junction.
- The transistor acts as a "Constant Current Source" when forward biased correctly.
- The resistance across the base-emitter junction is about

$$\mathbf{r_E = 25mv / I_E}$$

- Rule of Thumb → $I_C \sim I_E \sim 1$ma

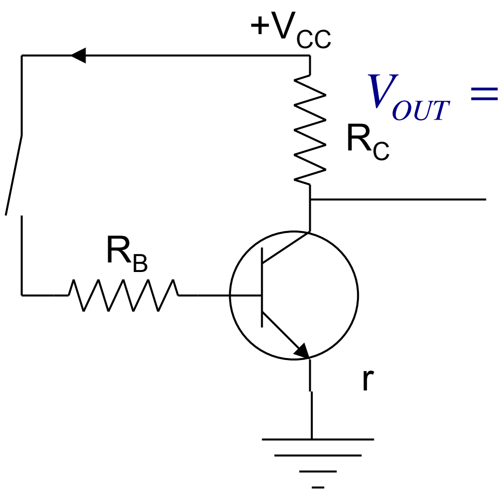
- Usually the input is "AC coupled" by inputing Vin through capacitor C. Only the AC component of a signal is passes!
- GAIN = Vout/Vin = $-R_C / R_E$ and Vout is180° inverted.
- Input impedance $r_{IN} = (1/R_1 + 1/R_2 + 1/\beta R_E)^{-1}$
if R1 and R2>>R_E $\mathbf{r_{IN} \sim \beta R_E}$
- $r_{OUT} \sim (1/R_C + 1/R_E)^{-1} \sim R_C$ looking into the output.
- $V_E \sim$ Vin – ~~0.7V~~ indicating small voltage drop across base-emitter junction.
- Vout = Vcc $-I_C R_C = V_C$



- Vout maximum ~ Vcc (power supply voltage)

Transistor Switch

- A transistor can be used as a robust switch to turn currents on and off.
- A small base current can control a large voltage supply current.
- When the switch is closed the transistor is driven in to saturation and acts as a short circuit.
- Transistors are useful switches when driving loads from high impedance sources (small current) such as microcomputers etc.
- Proper choice of R_B important to transistor life.



$$V_{OUT} = \begin{cases} V_{cc} & \textit{transistor OFF / OPEN} \\ 0 & \textit{transistor ON / CLOSED} \end{cases}$$

$$(I_C = 0 \ \ and \ \ Vout = Vcc)$$

$$Vout \sim I_C \underbrace{r_{transistor}}_{\sim 0} = 0$$

Biasing Resistors

$$I_B = V_{CC} / R_B$$

$$I_C = \beta \ I_B = \beta\left(V_{CC} / R_B\right)$$

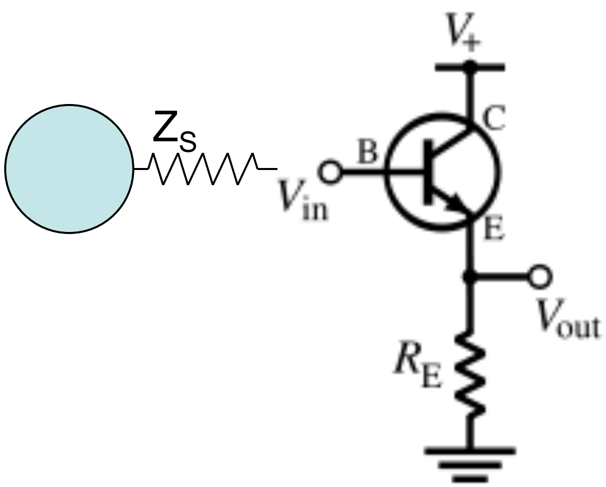
$$V_C = I_C R_C = \beta\left(V_{CC} / R_B\right) R_C$$

$$V_C / V_{CC} = \beta\left(R_C / R_B\right) \leq 1 \quad (Saturation!)$$

$$R_B \approx \beta R_C$$

Common Collector- Emitter Follower

• A emitter follower is a power booster circuit with unity gain.
• It is sometimes called a repeater or buffer amplifier.
• A small base current can be boosted to a large base current while preserving the signal shape, but significantly increasing the output power.
•The output is taken from the emitter.
•The emitter follower can be used to match a high impedance input to Low impedance output.



Output

1) $V_E = V_B - 0.6V$ $\qquad V_E \simeq V_B$ $\qquad \mathbf{V_{OUT} = V_{IN}}$

Input Impedance

(Im*pedance* – *to* – *ground seen looking in to base*)

1) $V_E / R_E \sim V_B / R_E = I_E = I_B + I_C = (1+\beta)I_B$

$V_B / R = (1+\beta)I_B$

2) $Z_{IN} = V_B / I_B = (1+\beta)R_E \sim \beta R_E$ $\qquad \boxed{Z_{IN} = \beta R_E}$

Output Impedance

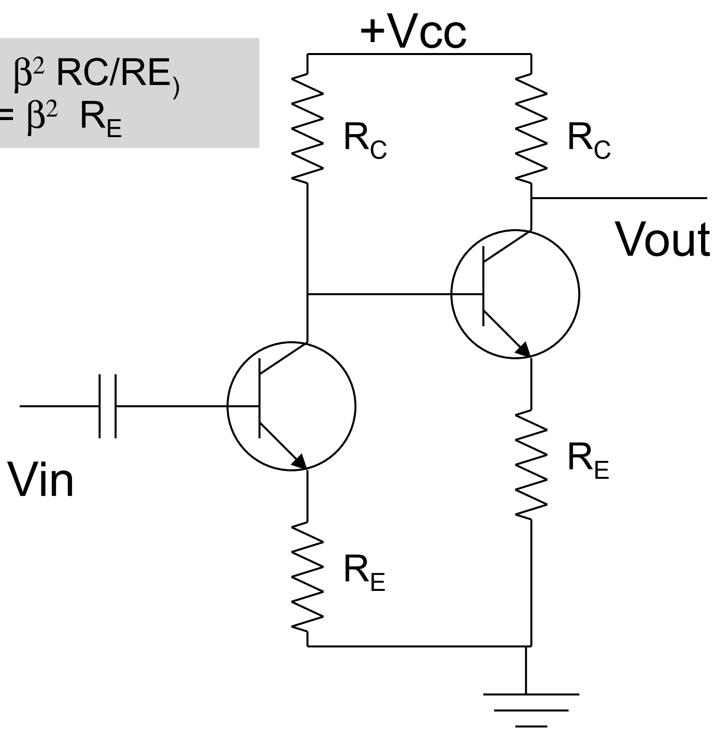
(*Effective series impedance at transistor output*)

$$\boxed{Z_{OUT} = Z_{SOURCE} / \beta}$$

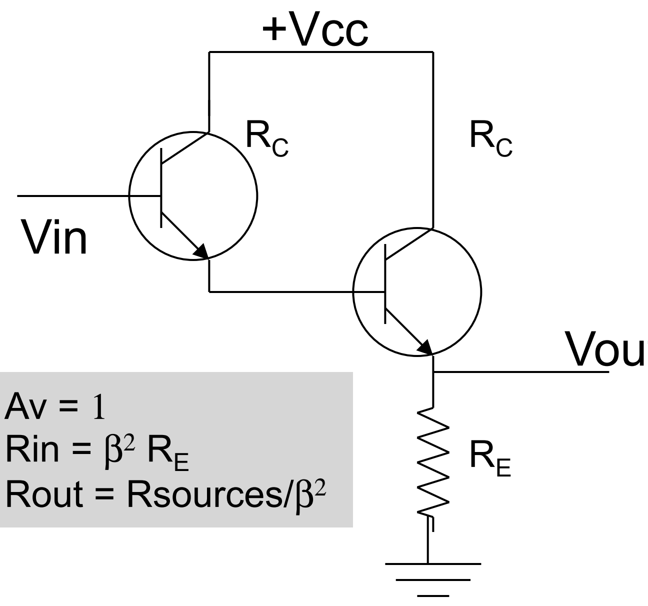
Cascading Amplifiers

- To achieve higher gain or input impedance we can cascade amplifiers output-to-input.

$A_v = \beta^2$ RC/RE)
$R_{in} = \beta^2\ R_E$



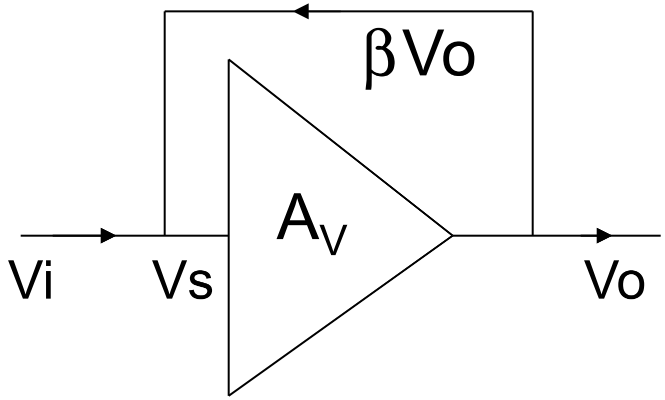
Darlington Pair



$A_v = 1$
$R_{in} = \beta^2 R_E$
$R_{out} = R_{sources}/\beta^2$

Feedback

- An amplifier may become more stable if a fraction of the output signal is fed back in to the input. (β=feedback fraction +/-)
- Positive feedback will enhance oscillatory behavior.
- Negative feedback will tend to cancel unwanted oscillatory behavior.



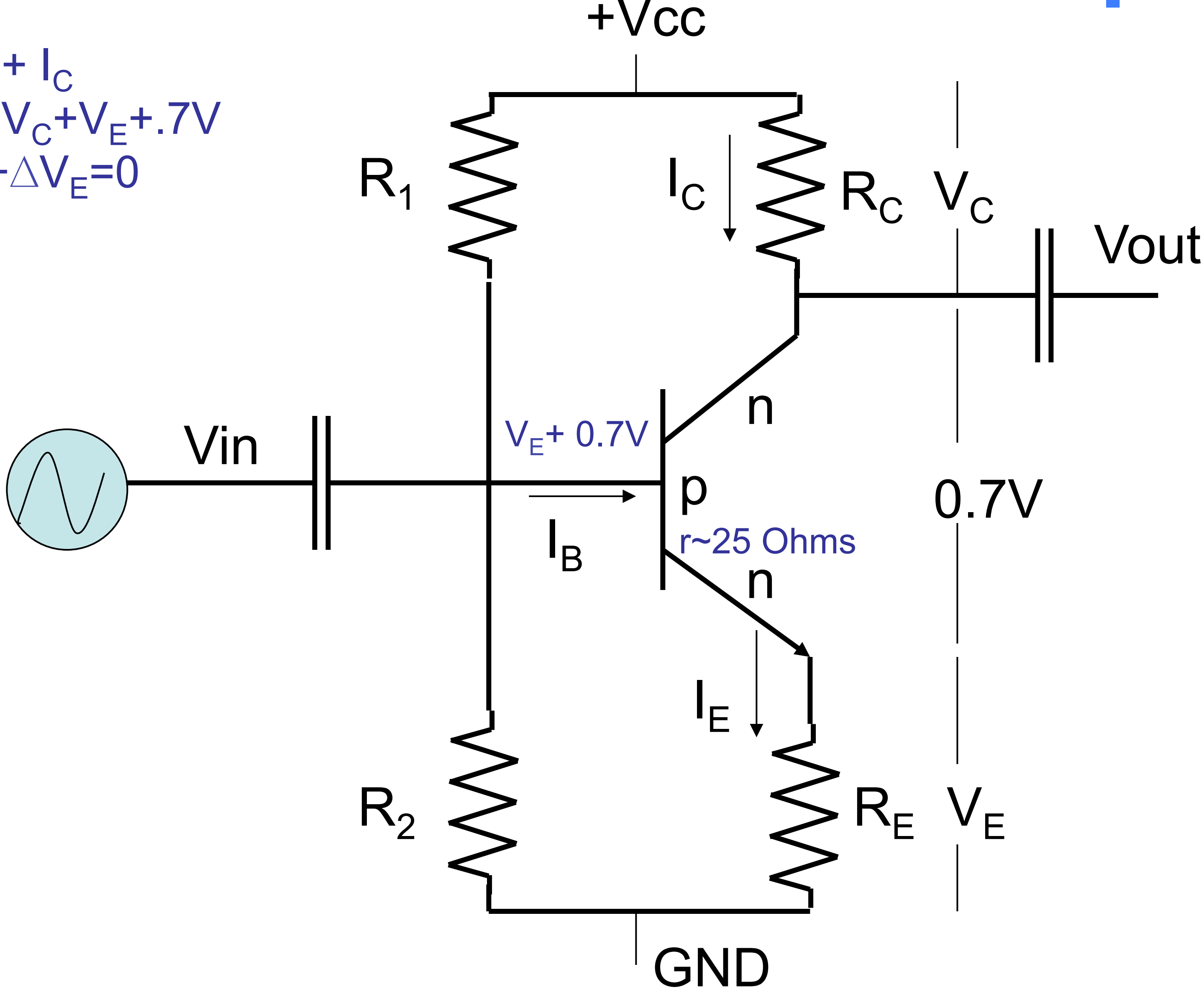
$\beta>0$ positive feedback oscillator

$\beta<0$ negative feedback stable amplifier

$$Vo = A_V Vs$$
$$Vs = Vi + \beta Vo$$
$$Vo = A_V(Vi + \beta Vo) = A_V Vi + \beta A_V Vo$$
$$Vo\,(1- \beta A_V) = Vi\,A_V$$
$$A'_V = Vo / Vi = A_V/(1- \beta A_V)$$

Basic Transistor Amp

$I_E = I_B + I_C$
$V_{CC} = V_C + V_E + .7V$
$\Delta V_C + \Delta V_E = 0$



Transistor Amp Design

- Set R_E by the input impedance. Zin = βR_E
- Set the R_C by the desired voltage gain. $|Av| = R_C / R_E$
- Set R_2 by the criteria that R_2 = 10% Zin = $\beta R_E /10$
  (R2 diverts most current away from the transistor)
- Set R1 by the amplifier gain Av and dynamic range of the power supply Vcc.

  $$Vb = 0.7V + (1/Av)\ Vcc / 2$$
  $$Vb = R2/(R1+R2)\ Vcc$$
  Solve for R1