Source follower
\[ Q_2 \text{ to bus source} \]

Common source (Q7)
\[ I_5 \text{ to load current for } Q7 \text{ (sink)} \]

(a) Current source
\[ Q_5 \text{ pushes current into circuit} \]

\[ V_{DD} \]
\[ V_{csmin} \]

\[ V_0 < V_{DD} - V_{csmin} \]

(b) Current sink

\[ V_0 \geq -V_{ss} \]
\[ V_{csmin} \]
\[ -V_{ss} \]

Active loaded = circuits that are current source loaded

Ch 6 & Bipolar Junction Transistor

NPN
\[ \text{npn} \]
\[ E \quad B \quad C \]

PNP
\[ \text{pnp} \]
\[ W \]

> Back to back pn junctions
> \[ W = \text{width of base which should be } \ll \text{ less than minority carrier length for interaction} \]
If $W$ is too large, just have back to back pn junctions and carriers from emitter all recombine in base and never make it to collector.

- Regions: Emitter (E), Base (B), Collector (C)
- EB and CB junctions

4 modes of operation for BJT

NPN transistor used for following charts

- EB forward bias
- CB reverse bias
- Forward active
- Cutoff
- EB, CB reverse biased

VBE
- EB, BC forward biased
- Saturation
- Reverse active
- CB forward biased
- EB reverse biased

NPN
- Cutoff
- Inverted active
- Active
- IB
- Ic
- Vce
- VBE
- Cutoff
Qualitative Description of forward active region of NPN

1) EB forward biased $\Rightarrow$ diffusion

\[ i_e \quad \overset{+}{\leftarrow} \quad n | p \quad \overset{-}{\rightarrow} \quad v \]

$\Leftarrow$ net current out of emitter

2) CB reverse biased $\Rightarrow$ drift of carriers from emitter
electrons from emitter diffuse through base and are swept into collector by reverse bias (are minority carrier in base)

\[ i_e \quad \leftarrow \quad n | p | n \quad \leftarrow \quad i_c \]

If almost all electrons from emitter go through base, collector current is slightly less than emitter current
3) Base current

- holes back injected across EB
  \[ \text{Junction} = i_{B1} \]
- holes that enter base to replace holes lost from base through recombination process = \( i_{B2} \)

Most transistors

emitter doping >> Base doping >> collector doping

I) Since emitter doping >> Base doping
\[ I_E \sim \text{electron current injected into base} \]

II) \( W << L_N \) (Diffusion length of electrons)
very few electrons lost as traverse base
Expressions for current flow through NPN transistor

(Need minority carrier concentration as function of position and differential equation)

1) Electron injection across EB junction

\[ I_n = A \cdot Q_0 \cdot D_n \left( \frac{-N_p(0)}{W} \right) \frac{dN_p}{dx} \]

- \( D_n, D_p \) are diffusion constants
- \( N_p(0) = N_{po} \exp \left( \frac{VBE}{V_T} \right) \)
- True for any forward biased junction (p-n)

2) Collector current

- If recombination is small, compared with injection current

\[ i_c = I_n = I_s \exp \left( \frac{VBE}{V_T} \right) \]

- \( I_s = A \cdot Q_0 \cdot D_n \cdot N_{po} / W \) saturation current

\[ \Rightarrow i_c \propto \text{indep of } VCB \text{ which is } > 0 \text{ (BC is reverse biased)} \]

- \( I_s \propto A \cdot N_i^2 \Rightarrow \) strong temperature dependence
3) Base current: hole injection into BE junction and hole recombination in base

\[ i_{B1} = \frac{AEQDP}{L_D} \frac{n_i^2}{N_D} \exp \left( \frac{V_{BE}}{V_T} \right) \]

\[ i_{B1} \ll I_E \text{ (mainly electron current in npn)} \]

hole recombination

\[ i_{B2} = \frac{Q_n}{T_B} \]

> \( Q_n \) = total # of e recombining with holes in base

> \( T_B \) = average time electrons survive before recombining

\[ i_{B2} \ll I_E \]

- Since \( W \ll L_n \)
- so few electrons are lost across base

\[ \Rightarrow \text{Driven by minority carrier concentration} \]

4) Emitter current

\[ i_\text{e} = i_B + i_c = \frac{B+1}{B} i_c = \frac{B+1}{B} I_s \exp \left( \frac{V_{BE}}{V_T} \right) \]

\[ B = \text{common emitter current gain} \]

Typical 50-100

\[ B = \left[ \frac{D_P}{D_n} \frac{N_A}{N_D} \frac{W}{L} + \frac{1}{2} \frac{W^2}{D_n P_P} \right]^{-1} \]

\[ \uparrow B, \downarrow W, \uparrow N_A / N_D \]

\[ i_c = \alpha i_e \quad \alpha = \frac{B}{B+1} \]

\[ i_c = \alpha i_e \]
\[ i_e = \frac{I_s}{\alpha} \exp \left( \frac{V_{BE}}{V_T} \right) \]

\[ B = \frac{i_c}{i_b} \]
\text{common emitter current gain}

\[ \alpha = \frac{i_c}{i_e} \]
\text{common base current gain}

**Summary of forward active (nnp)**

\[ i_c = I_s \exp \left( \frac{V_{BE}}{V_T} \right) \]
\[ i_B = \left( \frac{I_s}{B} \right) \exp \left( \frac{V_{BE}}{V_T} \right) = \frac{i_c}{B} \]
\[ i_e = \left( \frac{I_s}{\alpha} \right) \exp \left( \frac{V_{BE}}{V_T} \right) = \frac{i_c}{\alpha} \]

For large \( B \Rightarrow \alpha = 1 \)

**Large signal equivalent circuit model**
(for forward active)

\[ V_{BE} \quad (I_{SE} = \frac{I_s}{\alpha}) \]
6.1.4 NPN in saturation mode

BC & BE are both forward biased
Regime of operation for TTL devices

\[
\begin{align*}
\text{Border between saturation & forward active} & \\
& \begin{cases} 
V_{BC} = 0 & V_{BE} > 0 \\
\text{If } V_{BC} > 0.4V \Rightarrow BC \text{ junction is forward biased} \\
& \text{BC reduces total } I_c \\
& (\text{In active mode, } I_c \text{ is independent of } V_{BC}) \\
& i_c = I_s \exp \left( \frac{V_{BE}}{V_T} \right) - I_{sc} \exp \left( \frac{V_{BC}}{V_T} \right) \\
& \text{when } V_{BC} > 0.4V, \ i_B \text{ increased} \\
& B_{\text{forced}} = \left| \frac{i_c}{i_B} \right| \text{saturation} \leq B \\
& \text{can adjust } V_{BC} \text{ and can control } i_c/i_B
\end{cases}
\end{align*}
\]

Fig 6.8 (NPN)

\[
\begin{align*}
\text{satisfaction} & \rightarrow \ i_c \text{ active} \\
& \downarrow \ V_{CB}
\end{align*}
\]

Fig 6.9

\[
\begin{align*}
\text{isc} \exp \left( \frac{V_{BE}}{V_T} \right) & \rightarrow \\
& \text{DC} \\
& \uparrow \ i_c
\end{align*}
\]
Test for saturation mode

1) \( V_{BC} \geq 0.4 \text{V} \)

2) \( i_C/i_B < B? \)

\[ V_{CE\mid \text{sat}} = V_{BE} - V_{BC} \approx 0.1 - 0.3 \text{V} \]

CB larger area than EB \( \Rightarrow \)

\[ V_{BC} < V_{BE} \text{ by } 0.1 \text{ to } 0.3 \text{V} \]

Larger area \\ less voltage produces same current

Typically \( V_{CE\mid \text{sat}} = 0.3 \text{V} \) for edge of saturation

\( V_{CE\mid \text{sat}} = 0.2 \) for deep saturation

Cutoff : NPN

> \( EB, CB \) reverse biased

> thermally generated minority carriers (p) in emitter drift down potential into base (\( i_{IE} < 0 \))

> thermally generated minority carriers (p) in collector fall down into base (\( i_{IC} > 0 \))
Current is effectively zero

Inverted operation

> $V_{BC}$ is positive enough to reverse collector current ($I_C < 0$)
>
> Same physics as forward active but less efficient due to doping profile

PNP transistor just change signs

\[ \begin{align*}
  I_C & \rightarrow \text{holes} \\
  & \rightarrow \text{P} \\
  & \downarrow \\
  & \rightarrow \text{P} \\
  & \rightarrow I_C
\end{align*} \]

6.2 IV Characteristics and Circuit Symbols

Active mode

> EB forward biased

\[ V_{BE} < 0.4 \text{ V (npn)} \]

> Collector/Emitter reverse current

PNP
Substantial leakage larger than theory