Transistors

invented in 1947
- amplify current
- lower power consumption
- cheap for mass production
- robust to vibration
- long working time (decades) when properly used
- replaced vacuum tube
- building block of modern electronics

Some areas where vacuum tube are still good
- ultra high voltage applications (more then 1000 V)
- radiation prone locations

Bipolar junction Transistor (BJT)

NPN-transistor

PNP-transistor

Notation

- Base-emitter current ($I_{be}$)
- Collector-emitter current ($I_{ce}$)
- Base-emitter voltage difference ($V_{be} = V_B - V_E$)
- Collector-emitter voltage difference ($V_{ce} = V_C - V_E$)
Simple NPN-transistor rules

To support shown currents direction

- $V_{ce} > 0$
- $V_{be} > 0$
  - since, it is forward biased diode $V_{be} \approx 0.6 \text{ V}$
- $V_{cb} > 0$
  - since, it is reversed biased diode, no current goes from collector to base, all collector current is directed to emitter
  - if $V_{cb} < 0$ transistor goes to saturation and cannot be described by the following simple rule.

If above holds true then

- $I_{ce} = \beta I_{be}$
  - thus a BJT is a current amplifier
- the static forward current transfer ratio
  - $\beta$ (or sometimes $h_{fe}$) $\approx 100 \ldots 200$
- $I_e = I_{be} + I_{ce} = (\beta + 1) I_{be} \approx \beta I_{be}$
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the static forward current transfer ratio
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$I_{CE} = I_{BE} + I_{CE} = (\beta + 1)I_{BE} \approx \beta I_{BE}$
Simple PNP-transistor rules

Apply the same rules as before for NPN BJT but multiply currents and voltages by -1.

Hints
- the arrow indicates the direction in which current is supposed to flow.
- the arrow always connects the base and emitter.

Design considerations for $\beta$

Remember $\beta$ is not a constant!
It depends on many parameters
- temperature
- collector current
- varies from device to device even in the same batch

Good design should not depend on $\beta$ value.

Constant current source

Current through the load resistor does not depend on the load resistance.

$$I_L = I_C = \beta I_{BE} = \beta \frac{V_{CTRL} - 6V}{R_{SET}}$$

This is actually a sample of bad design since the current through the load depends on $\beta$. 

Notes
Constant current source

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This is actually a sample of bad design since the current through the load depends on \( \beta \).

\[ V_C = V_{cc} - R_L I_L \]

Remember that \( V_C \) must be \( > V_b \) thus current cannot be bigger than the saturation current

\[ I_{sat} = \max(I_L) \leq \frac{V_{cc} - V_b}{R_L} \approx \frac{V_{cc}}{R_L} \]

From \( V_{cc} \) point of view, left schematic is equivalent to the right one:

\[ R_{trans} = \frac{V_C}{I_L} = \frac{V_{cc} - R_L I_L}{I_L} \]

Transistor

\textbf{Trans(sform)-(r)esistor}

Constant current source. Power dissipation.

Transistor power dissipation

\[ P_{trans} = P_{be} + P_{ce} = V_{be} I_{be} + V_{ce} I_{ce} \]

Since

\[ V_{ce} \leq V_{ce}, I_{be} = \frac{I_{ce}}{\beta} \ll I_{ce}, \text{ and } I_{ce} = I_L \]

\[ P_{trans} = V_{ce} I_{ce} = R_{trans} I_L^2 \]
Constant current source. Power dissipation.

Transistor power dissipation

\[ P_{\text{trans}} = P_{\text{be}} + P_{\text{ce}} = V_{\text{be}}I_{\text{be}} + V_{\text{ce}}I_{\text{ce}} \]

Since

\[ V_{\text{be}} \leq V_{\text{ce}}, \quad I_{\text{be}} = I_{\text{ce}}/\beta, \quad \text{and} \quad I_{\text{be}} = I_L \]

\[ P_{\text{trans}} = V_{\text{be}}I_{\text{be}} = R_{\text{trans}}I_L^2 \]

Maximum power dissipation in transistor is when \( R_{\text{trans}} = R_L \).

Maximum power dissipation in transistor is when \( R_{\text{trans}} = R_L \max \)

\[ (P_{\text{trans}}) = \frac{V_{\text{cc}}^2}{4R_L}, \quad \text{when} \quad I_L = \frac{V_{\text{cc}}}{2R_L} \]

Voltage controlled switch

When properly designed outcome does not depend on reasonable variations of \( \beta \).

Recall that typically \( \beta = 100 \ldots 200 \)

We will assume the worst case scenario \( \beta = 10 \)

Notice that \( R_L \) limits collector current \( I_L \)

\[ I_L = \frac{V_{\text{cc}}}{R_L} \]

\[ I_{\text{be}} = \frac{V_{\text{cc}} - 6\text{V}}{R_B} = \frac{I_L}{\beta} \]

\[ R_B \leq \frac{V_{\text{cc}} - 6\text{V}}{\beta R_L} \]
We achieved the input impedance increase.

\[ R_{\text{input}} = \frac{V_{\text{in}}}{I_{\text{be}}} \approx R_L (\beta + 1) \]

As result our \( V_{\text{in}} \) source is not overloaded and our load receive all required current (as long as the collector power supply can support it).