Transistors.

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Week 6
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 than 1000 V)
- radiation prone locations
Bipolar junction Transistor (BJT)

NPN-transistor

PNP-transistor

Collector
N
P
N
Collector
C
E
Base
P
N
Base
B
E
Emitter
N
Emitter
P
N
Emitter
C
E

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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 \( h_{fe} \)) \( \approx 100 \ldots 200 \).

\[ I_E = I_{be} + I_{ce} = (\beta + 1)I_{be} \approx \beta I_{be} \]
Simple NPN-transistor rules

To support shown currents direction

- $V_{ce} > 0$

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 $h_{fe}$) $\approx 100\ldots200$

$I_e = I_{be} + I_{ce} = (\beta + 1)I_{be} \approx \beta I_{be}$
Simple NPN-transistor rules

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- $V_{be} > 0$
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$V_{be} > 0$

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\[ I_{ce} = \beta I_{be} \]

Thus a BJT is a current amplifier. The static forward current transfer ratio $\beta$ (or sometimes $h_{fe}$) $\approx 100\ldots200$.

\[ I_{e} = I_{be} + I_{ce} = (\beta + 1)I_{be} \approx \beta I_{be} \]
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$$I_{ce} = \beta I_{be}$$

thus a BJT is a current amplifier

the static forward current transfer ratio $\beta$ (or sometimes $h_{fe}$) $\approx 100 \ldots 200$

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- *the static forward current transfer ratio*
  \( \beta \) (or sometimes \( h_{fe} \)) \( \approx 100 \ldots 200 \)
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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 $h_{fe}$) $\approx 100 \ldots 200$
- $I_e = I_{be} + I_{ce} = (\beta + 1)I_{be} \approx \beta I_{be}$
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.

\[ I_L = I_c = \beta I_{be} = \beta \frac{V_{ctrl} - 0.6V}{R_{set}} \]
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 \( \beta \).
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\[ V_c = V_{cc} - R_L I_L \]
Current through the load resistor does not depend on the load resistance.

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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

\[ I_{sat} = \text{max}(I_L) \leq \frac{V_{cc} - V_b}{R_L} \approx \frac{V_{cc}}{R_L} \]
From $V_{cc}$ point of view, left schematic is equivalent to the right one.

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

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

\[ P_{\text{trans}} \approx V_{\text{ce}} I_{\text{ce}} = R_{\text{trans}} I_L^2 \]
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Maximum power dissipation in transistor
Constant current source. Power dissipation.

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Maximum power dissipation in transistor is when \( R_{\text{trans}} = R_{\text{L}} \)
Constant current source. Power dissipation.

Transistor power dissipation

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

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

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

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

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

\[
I_{be} = \frac{V_{ctrl} - .6V}{R_b} = \frac{I_L}{\beta}
\]

\[
R_b \leq \frac{V_{ctrl} - .6V}{V_{cc}} \beta R_L
\]
$V_{out} = V_{in} - 0.6V$

Gain. What gain?

We achieved the input impedance increase.

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

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

\[ V_{out} = V_{in} - 0.6V \]

Gain. What gain?

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

As a result, our \( V_{in} \) source is not overloaded and our load receives all the required current (as long as the collector power supply can support it).
Gain. What gain?
We achieved the input impedance increase.

\[ V_{out} = V_{in} - 0.6V \]

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

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