Transistor (transconductance resistor) is a three terminal device to switch or amplifier signals.

Idea:
Electronically control the main circuit
Voltage mode: high $V$: $R=0 \Rightarrow$ on
Low $V$: $R=\infty \Rightarrow$ off
Current mode: small current induces big current.

When the transistor is on

$V_{BE} > 0.6\, V$
$I = \beta i$

$V_{BE} < -0.6\, V$
$I \approx \beta i$

$NPN$
$I = (\beta+1)i \approx \beta i$

$PNP$
$\uparrow (\beta+1)i$
Rules for NPN transistor
1. Collector is more positive than Emitter.
2. Base-emitter and base-collector are effectively diodes.
3. $I_{\text{collector}} = \beta I_{\text{beta}}$. Beta can be as high as 60-100
4. Constraints: $I_{\text{base}}$, $I_{\text{collector}}$ and $V_{\text{ce}}$ should not be too high. Typically $I_{\text{collector}} < 0.1\sim 1$ A and $V_{\text{ce}} < 15\sim 40$V.

Model of a NPN transistor:

Applications:

1. Switch

   switch on: $I = 940mA$
   why?
   switch off: $I = 0$
Emitter follower: emitter follows the input (base), less one diode drop, with a factor of beta lower output impedance or higher input impedance:

\[ V_{in} = V_E \approx V_{in} - 0.6V \]

This is why it's called "Transimpedance resistor"!!

Impedance change: (Look at the purple circle)

Input impedance:

\[ Z_{in} = \frac{\Delta V_{in}}{\Delta I_{in}} \]
\[ = \frac{\Delta V_{out} R}{\Delta I_{in}} \]
\[ = (\beta + 1) R \]

Input impedance improved by \((\beta + 1)!!\)

Reminder: the higher the input impedance the better.
Output impedance: look at the orange circle

\[ Z_{\text{out}} = \frac{\Delta V_{\text{out}}}{\Delta I_e} = \frac{\Delta V_e}{\Delta I_e} = \frac{\Delta V_b}{(\beta+1) \Delta I_b} = \frac{r}{(\beta+1)} \]

Output impedance reduced by \((\beta+1)\).

A single transistor makes both input/output device happier by a factor of \(\beta+1\).

**Extension:**

**Darlington Pair:**

Further improve current amplification to

\[ \beta_{\text{eff}} = (1+\beta)(1+\beta') \]

Transistor as a current source

Transistor on:

\[ V_c = \beta i_b R + (\beta+1) i_b r \]

\[ \Rightarrow i_c = \beta^2 i_b \approx \frac{V_c}{R+r} \]

\[ V_b > 0.6 + (\beta+1) i_b r \]

\[ > 0.6 + V_c \frac{r}{R+r} \]

Transistor off:

\[ V < 0.6 + V_c \frac{r}{R+r} \]
Transistor as an amplifier:

\[ V_{out} = V_c - i_c R \]

\[ \approx V_c - i_e R \]

\[ = V_c - \frac{V_{in} - 0.6}{r} R \]

**What do we assume here?**

\[ G_{ac} = \frac{\delta V_{out}}{\delta V_{in}} \]

\[ = - \frac{R}{r} \]
Example: design a transistor amplifier with $G_a = 10$
for a weak signal with a power supply 10V.

Step 1: make sure it can amplify.

$$\delta V_{out} = -R \delta i_c$$
$$= -R \delta i_e$$
$$= -R \delta V_{in}/r$$
$$= -\frac{R}{r} \delta V_{in} = -10 \delta V_{in}$$
OK

Step 2: check the assumptions

$\delta i_c \approx \delta i_e$ fine

$\delta i_e = \delta V_{in}/r$ assumes what?

A. transistor is on $V_{be} = V_{in} - i_e r > 0.6 \Rightarrow V_{in} > 0.6 + i_e r$

B. $V_{in}$ cannot be too large: transistor can only be completely on.

$$\Rightarrow i_e < \frac{V}{R+r} = 9 \text{mA}$$

$$\Rightarrow V_{in} = 0.6 + i_e r < 0.6 + \frac{r}{R+r} V$$

Together we have 0.6 < $V$ < 0.6 + $\frac{1}{11}$ * 10 ≈ 1.5

So we should bias $V_{in}$ by, say, 1V, and thus

$i_e = 0.4/1K = 0.4 \text{mA}$. $V_{out}$ is biased by 6V

$V_{out} = 6 - 10 V_{in}$

*
A complete AC friendly circuit!

Our first non-trivial circuit!!