At the biasing polarity indicated above, the left pn-junction is biased forward, and the right one is biased in reverse. Thus, the holes from the left p-type zone are easily injected to the base, while holes from the right p-type zone cannot travel to the base. The electrons of the base cannot travel to the collector as well. On the contrary, the holes injected from the emitter into the base can easily go through the 2nd junction, because the built-in el. field ($E$) facilitates holes going to the collector.

Another important aspect is the carrier diffusion length, $L_{dif} = \sqrt{D \cdot \tau_{dif}}$, where $D$ is diff. coefficient and $\tau_{dif}$ is recombination limited carrier lifetime. In most doped semiconductors
The carrier diffusion length is typically
$L_{\text{diff}} \approx 100 - 300 \mu\text{m}$, that is $L_{\text{diff}}$ is large.
The physical width of the base region ($W_b$) is made thin intentionally, so that
$W_b < L_{\text{diff}} \approx 100 - 300 \mu\text{m}$. Typical $W_b \approx 100 \mu\text{m}$.
This allows holes passing through the
1st junction to reach the 2nd junction, where they are caught by the built-in
electrostatic field $E$ and hauled into the collector.
Only a very small fraction of holes injected from the emitter to the base end up
drained into the base contact. This fraction is usually just $0.1 - 1\%$.
This means that the collector current $I_c$ is almost equal to the emitter current $I_e$, and the
base current $I_b \ll \ll I_e, I_c$:

$$I_e = I_c + I_b,$$  \hspace{1cm} \text{Kirchhoff's current law}

Parameter $\beta = \frac{I_c}{I_b} \approx \frac{I_e}{I_b} = 10^2 \div 10^3 \gg 1$
$\beta$
$\beta$

Amplification factor
of transistor
What is the use of transistors (why do we need them)?

Let's first consider the problem of circuit loading.

DC voltage divider:

\[ V_{in} = 12V \]

\[ R_1 = 10 \, k\Omega \]

\[ R_2 = 10 \, k\Omega \]

\[ R_{in} = 1 \, k\Omega \]

When the external instrument is not connected, the current running through \( R_1 \) and \( R_2 \) is:

\[ I = \frac{V_{in}}{R_1 + R_2} = \frac{12V}{20 \, k\Omega} = 0.6 \times 10^{-3} \, A \]

and the potential at the midpoint is:

\[ V_{out} = I \cdot R_2 = 6V \]

However, when the external device is connected (this device has an input resistance \( R_{in} \), which is 1 \, k\Omega in our example), this device draws current, \( I_{in} \), which leads to modification of \( V_{out} \).
In this example \((V_{in} = 12\, V, R_1 = R_2 = 10\, k\Omega, r_{in} = 1\, k\Omega)\):

when the external circuit is connected,

\[
I_{total} = \frac{12\, V}{(10^4 + 10^3)\, \Omega} = 1.2 \times 10^{-3}\, A \quad \text{(that is, current increases almost twice!)}
\]

and

\[
V_{out} = R_{equiv} \cdot I_{total} = \frac{R_2r_{in}}{R_2 + r_{in}} \cdot I_{total} = \frac{10^4 \times 10^3}{10^4 + 10^3} \times 1.2 \times 10^{-3} = 1.2\, V \quad \text{(Instead of 6\, V!)}
\]

That's how much circuit loading modifies the output of the simple voltage source, such as a DC voltage divider.

More general expression for the output voltage in the case of loaded voltage divider is (derive as a homework):

\[
V_{out} = \frac{V_{in} \cdot \frac{R_2}{R_1 + R_2}}{1 + \frac{1}{V_{in} \cdot \frac{R_1R_2}{R_1 + R_2}}}
\]

This part is the ideal (not-loaded) voltage divider's output.

You can see that when \(V_{in}\) is \(\gg R_1R_2\) loading is small \((V_{out} \approx V_{in} \cdot \frac{R_2}{R_1 + R_2})\), but when \(V_{in}\) is small \(V_{out} < V_{in} \cdot \frac{R_2}{R_1 + R_2}\).
Transistor circuit that works as a better voltage source:

\[ V_{in} = 12V \]

\[ 12V \]

\[ V_{out} \]

\[ I_B - \text{base current} \]
\[ I_C - \text{collector current} \]
\[ I_E - \text{emitter current} \]
\[ \beta = \frac{I_C}{I_B} \approx \frac{I_E}{I_B} \gg 1 \]
\[ V_{in} = 12V \text{ is dc input} \]

**Figure:** Transistor circuit that is supposed to function as a good voltage source, meaning that it should provide more or less fixed output voltage \( V_{out} \) (measured across the load resistor \( R_e \)) irrespective of the value of the load resistance \( R_e \). NOTE: \( V_{out} \) as well as all other voltages are measured or applied with respect to the common ground.

According to the basic transistor properties, the base current must be extremely small compared to the collector and emitter currents, so that the amplification factor \( \beta \) is:
\[ \beta = \frac{I_C}{I_B} \approx \frac{I_E}{I_B} \gg 1 \] (typically \( \beta \approx 10^3 \)).

\[ I_B + I_C = I_E, \quad I_C \approx I_E \]

According to the voltage divider equation, base potential is:
\[ V_B = \frac{R_2}{R_1 + R_2} \cdot V_{in} \]

where \( V_{in} = 12V \) is a dc input voltage.

Then, \( V_{out} = I_E \cdot R_e = \beta I_B \cdot R_e = \beta R_e \cdot \frac{V_B - V_{out}}{R_e} \)

where \( R_e \) is the resistance of the pn-junction biased forward which is very low (\( R_e \) should be about 10–100 Ω).

Thus, by solving for \( V_{out} \) in the equation above, we get:
\[ V_{out} = \beta \cdot \frac{R_e}{R_e} \cdot \frac{V_B}{1 + \beta \cdot \frac{R_e}{R_e}} \]
\[ V_B = \frac{V_B}{1} = \frac{R_2}{R_1 + R_2} \cdot V_{in} \] (1).

This prefactor remains very close to 1, independently on \( R_e \) value, because \( \beta \gg 1 \) and \( R_e/R_e \gg 1 \), which reduces loading effects.
Transistor circuit that works as a better (more load independent) current source:

Fig. 4. Transistor circuit that is supposed to function as a good current source, meaning that it should provide more or less fixed collector current (flowing through the load resistor $R_L$), irrespective of the value of the load resistance $R_L$. NOTE: $V_{out}$ as well as all other voltages are measured or applied with respect to the common ground.

Here, as always, the transistor is trying to maintain large $\beta$, and hence $I_C \approx I_E$. By definition, $I_E = \frac{V_E}{R_E}$.

At the same time (see prev. page): $I_E = \beta I_E = \beta \frac{V_B - V_E}{R_E}$.

Hence, for $V_E$, we get: $V_E = \frac{\beta V_B \cdot R_E}{\beta R_E + R_E}$.

And for $I_E$, we get: $I_E = \frac{V_E}{R_E} = \frac{\beta V_B}{\beta R_E + R_E}$.

But $I_C = I_E \approx \frac{V_{in} - V_{out}}{R_L}$, and hence:

$$\frac{\beta}{R_E + \beta R_E} \cdot \frac{R_2}{R_1 + R_2} \cdot \frac{V_{in}}{R_L} = \frac{V_{out}}{R_L} \Rightarrow$$

$$V_{out} = V_{in} \cdot \left(1 - \frac{\beta R_2 R_L}{(R_1 + R_2) \cdot (R_E + \beta R_E)}\right),$$

and hence:

$$I_C \approx \frac{V_{in} - V_{out}}{R_L} = V_{in} \cdot \frac{\beta R_2}{(R_1 + R_2) \cdot (R_E + \beta R_E)} \approx V_{in} \cdot \frac{R_2}{(R_1 + R_2) \cdot R_E},$$

which is independent of $R_L$. 

$R_L$ is load resistor.