The Transistor as a voltage-controlled resistor

**nps bipolar transistor**

- **emitter**
- **base**
- **collector**

**2N2222**

*current in*

*current out*

*control knob*
As described, but turns on at 0.6V (for a Si diode).
Normally off (base/emitter reverse biased), small input current and voltage relative to emitter turns it on, switching and amplifying.

\[ I_C = \beta I_B \]
\[ I_E = I_C + I_B = (1 + \beta)I_B \]
\[ V_{BE} = V_B - V_E = +0.6V \]

\( \beta \sim 100 \), but changes with temperature and with \( V_{CE} \).
Transistor Switch

The collector current depends on the voltage drop across the bulb.

\[ I_C = \beta I_B \]

since the transistor state depends on the base current, leaving the base open circuited would eventually shut down the transistor, but this is sloppy.

\[ I_B = \frac{V_{CC} - V_{BE}}{R} \]
Transistor Switch

\[ V_{CC} = IR + V_{BE} \]
\[ I_B = \frac{V_{CC} - V_{BE}}{R} \]
\[ I_C = \beta \left( \frac{V_{CC} - V_{BE}}{R} \right) \]
\[ V_{BE} = 0.6V \]
What is $V_{out}$?

$V_{out} = V_{in} - 0.6V$

If the base/emitter is forward biased.
Emitter Follows as a Current Source #2

What is $V_{out}$ when the transistor is off?

![Diagram of transistor circuit with voltage levels and resistance values.](image)
Emitter Follows as a Current Source #3

At what base voltage does it turn off?

\[ V_{BE} = 0.6V \]
\[ \therefore V_{in} = -4.4V \]
Emitter Follows as a Current Source #4

\[ V_{out} = \begin{cases} 
V_{in} - 0.6V; & V_{in} \geq -4.4V \\
-5V; & V_{in} < -4.4V 
\end{cases} \]
Often signals are AC (or capacitively) coupled into amplifier stages. Note a single sided voltage supply can not amplify the negative inputs.
Biasing 2

Solve this by adding a DC to the base to shift the signal so that there is no clipping and AC coupling the output.

select $V_{CC} = 15V$

want $R_1 \parallel R_2 << \beta R_E$

$R_1 \parallel R_2$ is the impedance of the current source used to drive the transistor, $\beta R_E$ is the effective impedance of the base of the transistor.

Rule: make the impedance of the source small compared to the load it drives.
Biasing 3

\[ V_{CC} = 15V, \ R_1 \parallel R_2 \ll \beta R_E \]

- want the output to swing ±7.5V
- select \( R_E = 7.5k\Omega \)

\[ V_{E} @ (\approx 0) = 7.5V \text{(allows } V_{out} \text{ to swing } \pm 7.5V) \text{ then } V_B = V_E + 0.6V = 8.1V \]

\[
\frac{R_2}{R_1 + R_2} = \frac{8.1V}{15V} \quad \text{or} \quad \frac{R_1}{R_2} = \frac{1}{1.17}
\]

- \( R_1 \parallel R_2 \ll \beta R_E \ll 100 \times 7.5k\Omega \)

\[ R_1 = 130k\Omega, \ R_2 = 150k\Omega \]
Demo: BJT Emitter Follower #1

- Oscillator
- Frequency/Amplitude
- Dual Voltage Source 12V
- 33kΩ Resistor
- 1kΩ Resistor
- Input #1: Vin
- Input #2: Vout
- Time Base Display
- Oscilloscope
- Trigger

Components:
- Voltages: Vin, Vout
- Resistors: 33kΩ, 1kΩ
- Sources: 12V Dual Voltage Source
Demo: BJT Emitter Follower #2

oscillator
Frequency amplitude
V_n
33kΩ
1kΩ
V_out
Input #1
Input #2
V_in
V_out
dual voltage source
12V
oscilloscope
x,y display
1kΩ
V_in
6.071 Bipolar Transistors
Emitter Follower

The output voltage is almost the base voltage, with a 0.6 V cutoff. Notice the change in impedance.

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

\[ R_{in} = \beta R_{load} \]

\[ V_{out} \]

\[ \text{VCC} \]

\[ R_{load} \]

\[ V_B \]
The Emitter Follows Has Unit Voltage Gain; Is it Useless?

\[ \Delta V_{in} = \Delta V_{out} \]

Note: \[ \Delta I_E = \frac{\Delta V_{out}}{R} = \frac{\Delta V_{in}}{R} \]

and \[ \Delta I_B = \frac{\Delta I_E}{1 + \beta} = \frac{\Delta V_{in}}{R(1 + \beta)} \]

\[ P = IV \quad \therefore P_{in} = \frac{V_{in}^2}{R(1 + \beta)}; P_{out} = \frac{V_{in}^2}{R} \]

There is a gain in Power of \( \beta \).

The effective base resistance is \( \beta R \).
Don’t design with $\beta$

Here the quiescent point was selected by bleeding a small amount of current into the base. Now the operating point depends critically on $\beta$ which varies tremendously from device to device and with temperature.
Problem: Look at last circuit as $\beta$ is varied from 100 to 200.
Current Source

The base voltage controls the current through the load up to the limit of $V_{CC}$.

\[
V_E = V_B - 0.6V
\]
\[
I_E = \frac{V_E}{R}
\]
\[
I_{load} = I_C = \frac{V_B - 0.6V}{R}
\]
\[
I_C \equiv I_E, \text{ for large } \beta
\]
The common emitter configuration provides a (negative) voltage gain. (1)
Set the quiescent current such that
\[ V_C = \frac{V_{CC}}{2} \rightarrow \text{Want a voltage drop of } V_C \text{ over } R_C. \]
\[ \therefore I_C = I_q = \frac{V_C}{R_C} = \frac{V_{out}}{R_C}; \]
\[ I_B = \frac{V_{in}}{\beta R_E} = \frac{I_C}{\beta}; \]
\[ \therefore \frac{V_{out}}{V_{in}} = -\frac{R_C}{R_E}. \]
So $R_C = \frac{V_{CC}}{2I_q}$.

Gain = $-\frac{R_C}{R_E}$

$R_E$ is necessary for stability, otherwise there is a small resistance $r_o \sim 0.026V/I_E$, but this is very temperature sensitive.
If the source output impedance is much lower than the load input impedance than the circuit performance will be independent of load variation. Therefore in a multi-stage device, if we use a FET as the building blocks of the load, the input impedance of the load will be high and we will have a robust circuit.
Voltage Transfer

\[ V_L = \frac{R_L}{R_L + R_{th}} V_{th} \]

so if \( V_L \approx V_{th} \)

\[ R_{th} \ll R_L \]

For efficient voltage transfer, keep the load impedance larger than the source impedance.

Two exceptions:

- Radio Frequency circuits, \( Z_{source} = Z_{load} \) (provide maximum power transfer)
- Coupling currents rather than voltages.
\[ I_L = \frac{R_N}{R_L + R_N} I_N \]

so if \( I_L \sim I_N \)

\[ \therefore R_N \gg R_L \]

For efficient current transfer keep the load impedance small compared to the source impedance.
Power Transfer #1

\[ V_L = \frac{R_L}{R_L + R_{th}} V_{th} \]

\[ I = \frac{V_{th}}{(R_L + R_{th})} \]

\[ P_L = V_L I = \frac{R_L}{(R_L + R_{th})} V_{th} \times \frac{V_{th}}{(R_L + R_{th})} = \frac{R_L V_{th}^2}{(R_L + R_{th})^2} \]
\[ I_L = \frac{R_N}{R_L + R_N} I_N \]
\[ P_L = I_L^2 R_L = \frac{R_N^2 I_N^2 R_L}{(R_L + R_N)^2} \]
Unity-gain phase splitter

goal: from an AC signal generate a copy and its inverse.

\[
\begin{align*}
V_{out}^- &= -V_{in}(+) \\
V_{out}^+ &= V_{in}(+)
\end{align*}
\]

\[V_{out}^+ \equiv \text{emitter follows}\]
\[\therefore \text{unity gain}\]

\[V_{out}^- \equiv \text{common emitter}\]
\[\therefore \text{with } R_C = R_E, \text{ gain} = -1\]
• choose $V_E = 5\text{V}$
  $\therefore V_B = 5.6\text{V}$

since $I_C \approx I_E$, there is a drop of $5\text{V}$ over both $4.7\text{k}\Omega$ resistors.
Darlington Pair

Useful for large current applications, and high input impedance. They are slow, however. Base to Emitter drop is 1.2 V.
Transistors form the basis of logic gates, and of integrated circuits.

<table>
<thead>
<tr>
<th>$A_{in}$</th>
<th>$B_{in}$</th>
<th>out</th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>low</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>high</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
</tbody>
</table>
Transistor OR Gate

<table>
<thead>
<tr>
<th>$A_{in}$</th>
<th>$B_{in}$</th>
<th>out</th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>low</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>high</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
</tbody>
</table>
Properties of Bipolar Transistors

\( \beta \) (current gain) is not a parameter, it varies with everything.

- \( I_{C,\text{max}} \) - maximum collector current rating.
- \( BV_{CBO} \) - maximum collector to base voltage.
- \( BV_{CEO} \) - maximum collector to emitter voltage.
- \( V_{EBO} \) - emitter to base breakdown voltage.
- \( P_D \) - maximum collector power dissipation.
Datasheet of 2N2222 (1 of 3)

PN2222A  MMBT2222A  PZT2222A

NPN General-Purpose Amplifier
This device is intended for use in general-purpose amplifier and switch applications where collector currents up to 200 mA and collector voltages up to 50 V are required.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vceo</td>
<td>Collector-Base Voltage</td>
<td>65</td>
<td>V</td>
</tr>
<tr>
<td>Ic</td>
<td>Collector Current</td>
<td>100</td>
<td>mA</td>
</tr>
<tr>
<td>Ie</td>
<td>Emitter Current</td>
<td>100</td>
<td>mA</td>
</tr>
<tr>
<td>Pd</td>
<td>Power Dissipation</td>
<td>1.5</td>
<td>W</td>
</tr>
<tr>
<td>Hfe</td>
<td>Common-Mode Gain</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Phase Angle and Cross-Over Frequency</td>
<td>1 MHz</td>
<td></td>
</tr>
</tbody>
</table>

*Note: These specifications are for reference only and may vary depending on the specific application and environmental conditions.
### Datasheet of 2N2222 (2 of 3)

#### Thermal Characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Characteristic</th>
<th>Min</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tja</td>
<td>Case Temperature Junction to Ambient</td>
<td>50</td>
<td>75</td>
<td>°C</td>
</tr>
<tr>
<td>Vbe</td>
<td>Base-Emitter Saturation Voltage</td>
<td>0.65</td>
<td>0.95</td>
<td>V</td>
</tr>
<tr>
<td>Rsat</td>
<td>Base Resistance Saturation</td>
<td>100</td>
<td>200</td>
<td>kΩ</td>
</tr>
<tr>
<td>Tc</td>
<td>Collector Temperature</td>
<td>100</td>
<td>150</td>
<td>°C</td>
</tr>
</tbody>
</table>

#### Electrical Characteristics

### NPN General Purpose Amplifier (continued)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Test Conditions</th>
<th>Min</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ic</td>
<td>Collector Current</td>
<td>Vcc = 5V, Vbc = 0V</td>
<td>0.5</td>
<td>1.0</td>
<td>mA</td>
</tr>
<tr>
<td>Vbe</td>
<td>Base-Emitter Voltage</td>
<td>Vcc = 5V, Vbc = 0V</td>
<td>0.65</td>
<td>0.95</td>
<td>V</td>
</tr>
<tr>
<td>Rsat</td>
<td>Base Resistance Saturation</td>
<td>100</td>
<td>200</td>
<td>kΩ</td>
<td></td>
</tr>
<tr>
<td>Vcb</td>
<td>Collector-Base Voltage</td>
<td>Vcc = 5V, Vbc = 0V</td>
<td>30</td>
<td>40</td>
<td>V</td>
</tr>
<tr>
<td>Isat</td>
<td>Saturation Current</td>
<td>Vcc = 5V, Vbc = 0V</td>
<td>10</td>
<td>15</td>
<td>mA</td>
</tr>
</tbody>
</table>

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6.071 Bipolar Transistors
### ON CHARACTERISTICS

<table>
<thead>
<tr>
<th>Spec</th>
<th>Parameter</th>
<th>Unit</th>
<th>200 mA</th>
<th>300 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vcesat</td>
<td>Collector-emitter saturation voltage</td>
<td>V</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Icesat</td>
<td>Saturation collector current</td>
<td>mA</td>
<td>100</td>
<td>150</td>
</tr>
</tbody>
</table>

### SMALL SIGNAL CHARACTERISTICS

<table>
<thead>
<tr>
<th>Spec</th>
<th>Parameter</th>
<th>Unit</th>
<th>200 mA</th>
<th>300 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vce</td>
<td>Collector-emitter voltage</td>
<td>V</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Vbe</td>
<td>Collector-emitter voltage</td>
<td>V</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Vbe</td>
<td>Emitter-base voltage</td>
<td>V</td>
<td>0.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>

### ELECTRIC CHARACTERISTICS

<table>
<thead>
<tr>
<th>Spec</th>
<th>Parameter</th>
<th>Unit</th>
<th>200 mA</th>
<th>300 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rbe</td>
<td>Base-emitter resistance</td>
<td>kΩ</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Rbe</td>
<td>Emitter-base resistance</td>
<td>kΩ</td>
<td>100</td>
<td>150</td>
</tr>
</tbody>
</table>

**Datasheet of 2N2222 (3 of 3)**
A simple voltage regulator.

Poor ripple suppression, requires a zener with high power rating, and variations with load impedance.

Zeners are diodes that have variable resistance. Specifically, zeners have a constant current output over a range of input voltages. Thus, by providing a constant current to a circuit, zeners can be used as voltage regulators.

Vin

Vout = Vzener

Real Zener

Ideal Zener
Voltage Regulator

\[ V_{\text{out}} = V_{\text{zener}} - 0.6 \text{ V} \]

Emitter follower configuration.
Base current is only \( \frac{1}{\beta} \) of supply current.
RC filter reduces ripple.
Switching inductive loads

The voltage kick from interrupting current flow in an inductor can lead to voltage breakdown in the transistor. A backwards diode across the inductive load shorts this out.
Common Collector Amplifier

An amplifier with a current gain (no voltage gain) and offset to avoid clipping negative inputs.

R₁ and R₂ provide the DC offset and C₁ acts as a filter (so inputs do not disturb quiescent point).
1. choose a quiescent current, 1 mA
2. $V_E = \frac{V_{cc}}{2}$
   (allows the largest symmetric input).

$$R_E = \frac{V_{cc}/2}{I_Q} = \frac{V_{cc}/2}{1mA}$$
3. Set the quiescent current via $R_1$ & $R_2$.

$$\frac{R_1}{R_2} = \frac{V_{CC} - V_B}{V_B} = \frac{V_{CC} - V_E - 0.6V}{V_E + 0.6V}$$

recall: $V_E = V_{CC}/2$

So, forget 0.6V and $R_1 = R_2$

$R_{\text{load}}$ Note that $R_{\text{base}} = \beta R_E$, so $R_1||R_2 < \beta R_E$

prevents the quiescent point from shifting with load.
4. Choose coupling capacitors

The effective AC input resistance

\[ R_{in} = R_1 \parallel R_2 \parallel (R_E \parallel R_{load}) \]

\( C_1 \) and \( R_{in} \) form a high-pass filter

\[ C_1 = \frac{1}{\omega_{3dB} R_{in}} \]

\( C_2 \) and \( R_{load} \) also form a high-pass filter

\[ C_2 = \frac{1}{\omega_{3dB} R_{load}} \]
Common Collector Amplifier

- $V_{CC}$
- $R_1$
- $V_B$
- $C_1$
- $R_2$
- $R_E$
- $R_{load}$

- Base voltage
- Output
- Frequency response