EEE118: Electronic Devices and Circuits
Lecture XVI

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

- Gave an example of calculation of circuit two's DC conditions.
- Discussed the design of biasing circuits
  - Noted that there is (almost) always some compromise required.
- Looked in detail at coupling and decoupling in the two bias circuits.
  - Coupling - signals in to or out of the circuit.
  - Decoupling - signals shorted to ground where they are unwanted.
- Developed a small signal model for the BJT / MOSFET / JFET / Valve.
  - Looked at the transconductance amplifier / current amplifier duality of BJTs.
 - Derived some key small signal relationships for BJT circuit from the transconductance characteristics.

Outline

Feedback of Signals in Amplifiers Without Emitter De-coupling

—— Voltage across a component
—— Voltage from node to ground
—— Current through a branch

I_{C_T} and I_{E_T} are formed from a DC component I_C and I_E and an AC (small signal) component i_c and i_e.

EEE118: Lecture 16
└ Feedback for Quiescent and Signal Conditions
  └ Feedback of Signals in Amplifiers with Emitter De-coupling

Feedback of Signals in Amplifiers with Emitter De-coupling

Voltage across a component
Voltage from node to ground
Current through a branch
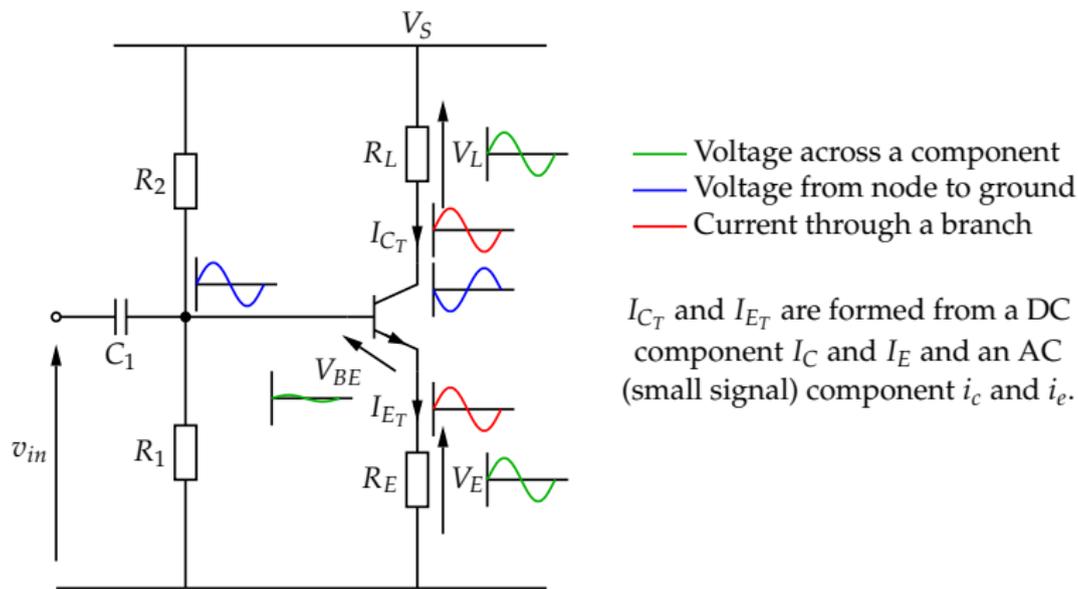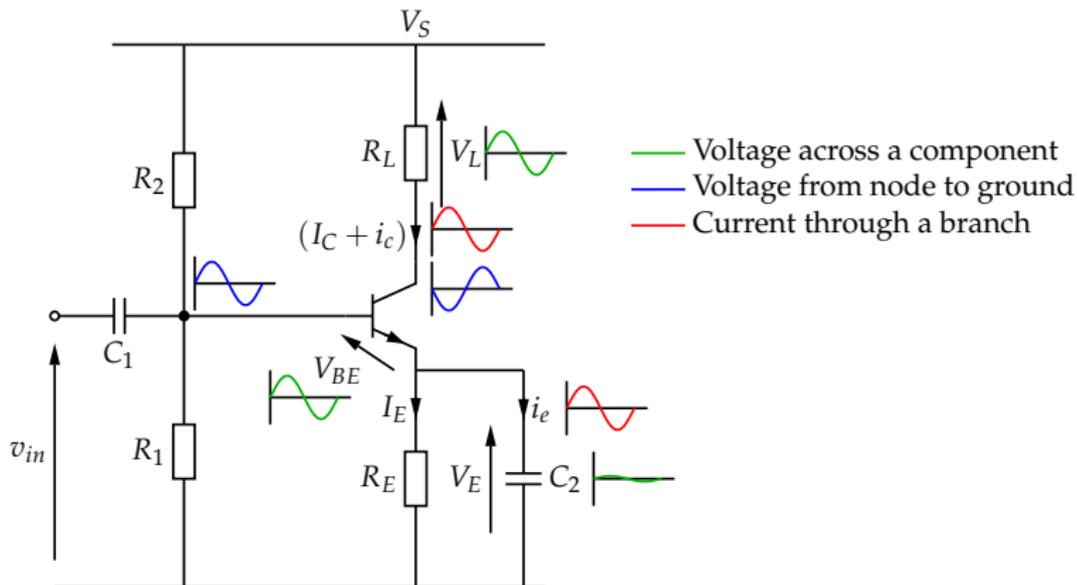
1. A signal voltage is impressed on the base with respect to ground (blue)

2. causing a voltage to appear across the base - emitter junction (green)

3. which in turn causes a current in the collector (red)

4. The collector current flows in the emitter also ($i_b = 0$) (red)

5. The emitter resistor drops a voltage, $v = i\,R_E$ (green)

6. Since V_{R_1} is fixed by V_{in} and the ratio of R_1 & R_2, v_{be} must reduce.

The feedback for signals is undesirable so it is removed by de-coupling the emitter resistor ($Z_E = R_E // \frac{1}{2\pi f\,C_2}$), where C_2 is large enough to dominate Z_E at all frequencies of interest. The feedback for DC conditions is desirable, as it stabilises the operating point. The capacitive de-coupling does not affect the DC conditions because the de-coupling capacitor looks like an open circuit at DC and $Z_E = R_E$.
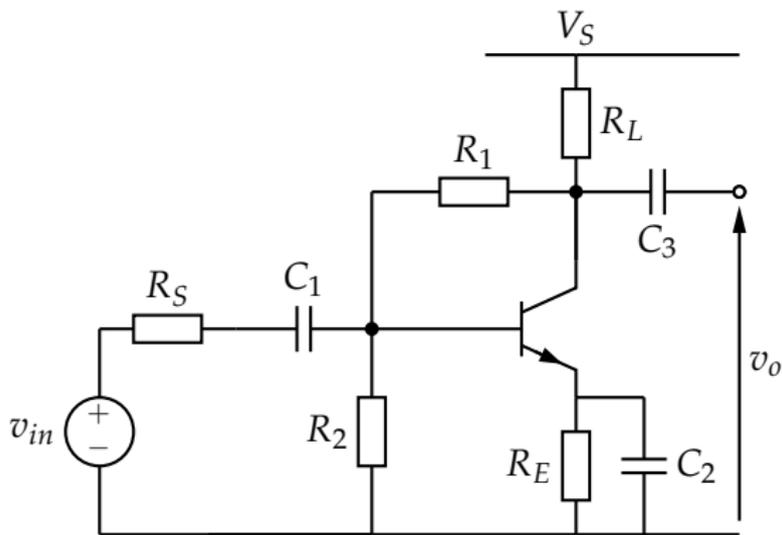
Drawing the Small Signal Equivalent Circuit

To draw the small signal diagram think about how the signal "sees" the circuit. There are several consequences of considering how the circuit looks to the signal.

- All DC voltage sources (power supplies etc.) are replaced by their Thévenin equivalent impedance (0 Ω).
- All DC current sources are replaced by their Norton equivalent impedance (∞ Ω).
- In small signal problems - in this course - capacitors can often be thought of as open circuit to DC and short circuit to AC.
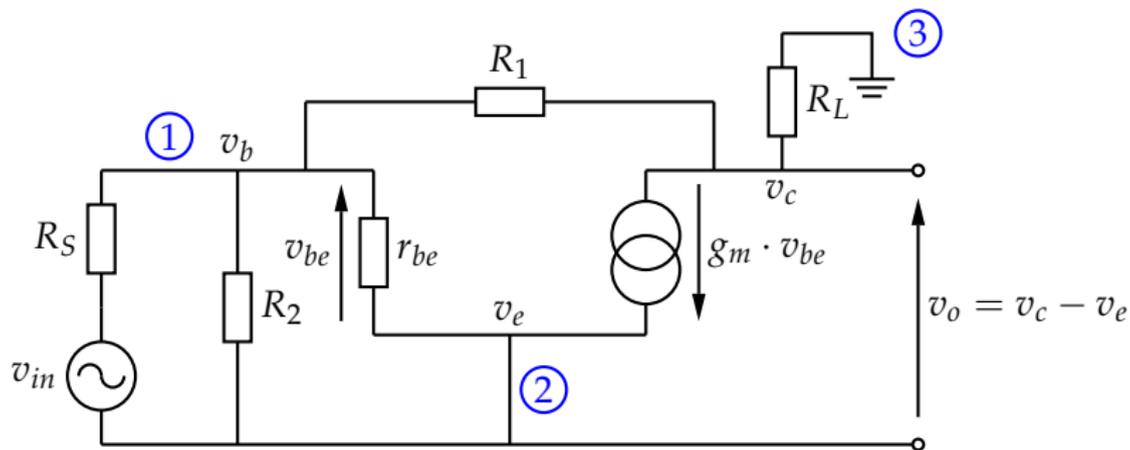
Holding these guidelines in mind, the transistor is replaced terminal for terminal by its small signal model.
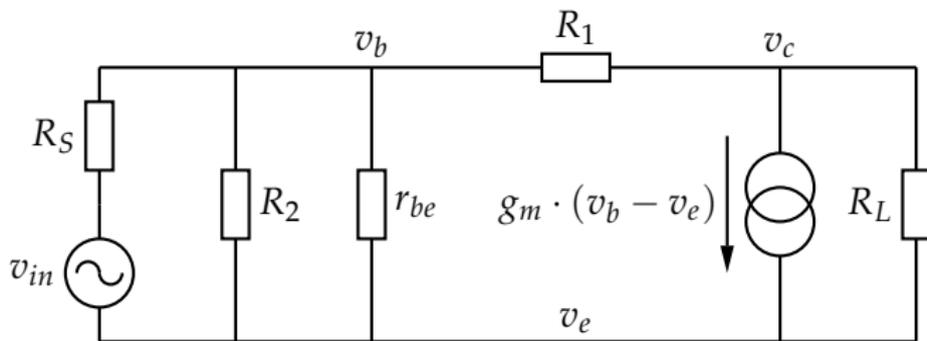
An Example Small Signal Circuit Problem

Draw the small signal circuit diagram for the following transistor amplifier,

Solution

1. C_1 looks like a short circuit.

2. C_2 looks like a short circuit, and de-couples R_E.

3. V_S looks like a connection to ground from the signal's point of view.

Remember that the small signal equivalent circuit varies according to the circuit it tries to represent. It is unwise to learn this result. It is wise to learn the skills needed to construct the small signal circuit from the full diagram.

Having arrived at the small signal equivalent circuit, the small signal performance of the circuit can be assessed.

Performance Analysis

What is the voltage gain, $\frac{v_o}{v_{in}}$?

Summing currents at the collector (output) node (note $v_e = 0$!),

$$\frac{v_c - v_e}{R_L} + \frac{v_c - v_b}{R_1} + g_m\left(v_b - v_e\right) = 0 \tag{1}$$

Summing currents at the input node,

$$\frac{v_s - v_b}{R_s} + \frac{v_c - v_b}{R_1} = \frac{v_b}{R_2} + \frac{v_b}{r_{be}} \tag{2}$$

(1) can be transposed to yield,

$$v_b = -\frac{v_c\left(R_1 + R_L\right)}{g_m\,R_1\,R_L - R_L} \approx -\frac{v_c}{g_m\,R_1//R_L} \tag{3}$$

provided $g_m\,R_1 >> 1$ which is usually true.

(2) can be transposed to yield,

$$v_b = \frac{\frac{v_s}{R_S} + \frac{v_s}{R_1}}{\frac{1}{R_2} + \frac{1}{r_{be}} + \frac{1}{R_S} + \frac{1}{R_1}} \tag{4}$$

$$= \frac{v_s \left(R_2//r_{be}//R_S//R_1 \right)}{R_S} + \frac{v_c \left(R_2//r_{be}//R_S//R_1 \right)}{R_1} \tag{5}$$

eliminating v_b and transposing to obtain $\frac{v_c}{v_s}$,

$$\frac{v_c}{v_s} = -\frac{R_1}{R_S} \cdot \frac{1}{1 + \frac{R_1}{(g_m R_1//R_L)(R_2//r_{be}//R_S//R_1)}} \tag{6}$$

The value of this result is chiefly that it can tell us how the small signal voltage gain depends on the circuit and transistor parameters. It can be used to estimate gain, but computer simulation packages like SPICE are more suited to this. In this case if $\frac{R_1}{(g_m R_1//R_L)(R_2//r_{be}//R_S//R_1)} << 1$ the gain is controlled by the resistors R_1 and R_S, and is largely independent of transistor parameters like g_m and r_{be}.

The feedback caused by R_1 can be removed by setting $R_1 \to \infty$. R_1 disappears from the parallel combinations to yield,

$$\frac{v_c}{v_s} = -\frac{R_1}{R_S} \frac{1}{1 + \frac{R_1}{g_m R_L (R_2 // r_{be} // R_S)}} \tag{7}$$

Since R_1 is very large, the $\frac{R_1}{g_m R_L (R_2 // r_{be} // R_S)}$ term will dominate the denominator giving,

$$\frac{v_c}{v_s} = -\frac{R_1}{R_S} \frac{1}{\frac{R_1}{g_m R_L (R_2 // r_{be} // R_S)}} = -g_m R_L \frac{R_2 // r_{be}}{R_S + R_2 // r_{be}} \tag{8}$$

This expression consists of a gain term, $g_m R_L$ and an input potential division, $\frac{R_2 // r_{be}}{R_S + R_2 // r_{be}}$. The circuit gain is now dependent on the transistor parameters g_m & r_{be}. The negative feedback effect of R_1 has been removed.

In removing R_1, the circuit has been changed from a small signal equivalent circuit of "circuit two" to "circuit one". The R_1 in circuit one, which is necessary for the correct biasing of the transistor, appears in parallel with R_2 in the small signal model (remember that the V_S rail is small signal ground). Hence adjusting the value of R_1 in circuit one will change the effective value of R_2 (they appear in parallel), but will not change the small signal diagram.

Each circuit shape produces its own result for gain and other performance measures so memorising these results is not wise - learning *how* to derive them and interpret their meaning is...

Some other metrics of performance that can be derived are, input impedance ($\frac{v_s}{i_s}$), output impedance (drive a test current i_t into the collector and find the effect on v_c) and power gain, among others.

Homework 4

It should be possible to *fully* attempt the Homework 4 now.

It should also be possible to fully attempt the Rectifiers and Smoothing problem sheet.

It should also be possible to fully attempt the Transistors as Switches and Amplifiers problem sheet.

Operational Amplifiers (Opamps)

- An Opamp is an integrated circuit composed of between 10 and ∼50 transistors (BJT, MOS or JFET) which implements certain functionality making it useful as an "analogue building block".

- Opamps have been in use since about 1930, the originals being valve based.

- Opamps are designed to have,
    - differential inputs (two inputs which it subtracts)
    - very high input resistance ($> 10^9\ \Omega$)
    - very low output resistance ($< 50\ \Omega$)
    - very high gain ($\sim 10^5$ is typical)

Opamps are designed to be used with feedback. Therefore, some discussion of feedback is required to understand opamps.

A Classical Feedback System

To understand why the opamp is designed to have the features outlined on the last slide consider a classical feedback system.
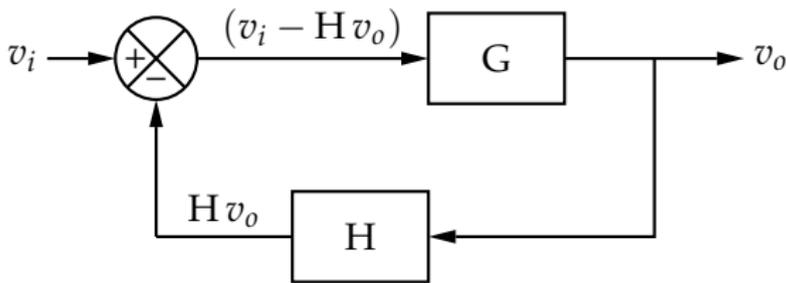
- The output voltage is v_o.
- A portion of the output, $H v_o$, is fed back to the input.
- This portion is subtracted from v_i,
- leaving $(v_i - H v_o)$ at the input of the gain stage, G.

We can write these statements in the form of an equation,

$$v_o = G\,(v_i - H\,v_o) \tag{9}$$

or,

$$\frac{v_o}{v_i} = \text{ gain } = \frac{G}{1 + G\,H} \tag{10}$$

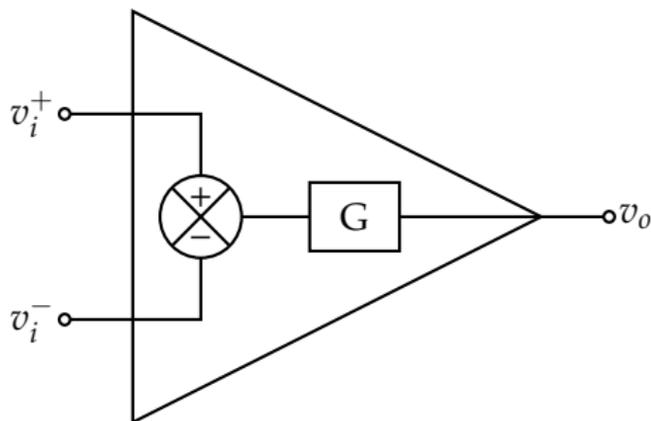If G is very large, then $G\,H >> 1$ and,

$$\frac{v_o}{v_i} \approx \frac{G}{G\,H} = \frac{1}{H} \tag{11}$$

This is an interesting result because it shows that if G is very large, the system gain depends only on H.

H is usually defined by resistors and capacitors - which the designer has a high degree of control over. Only resistors in EEE118.

The Opamp

The opamp integrates two parts of the classical feedback system.

- The input resistance must be high so that the v^- input does not affect the network that defines H and so that the v^+ input does not affect the signal source.

- The output resistance must be low so that the system can drive a load without v_o begin affected and so that the system can drive the network defining H without being affected.
- The reason for the differential input and the high gain are shown by (11).

The opamp is usually drawn as,
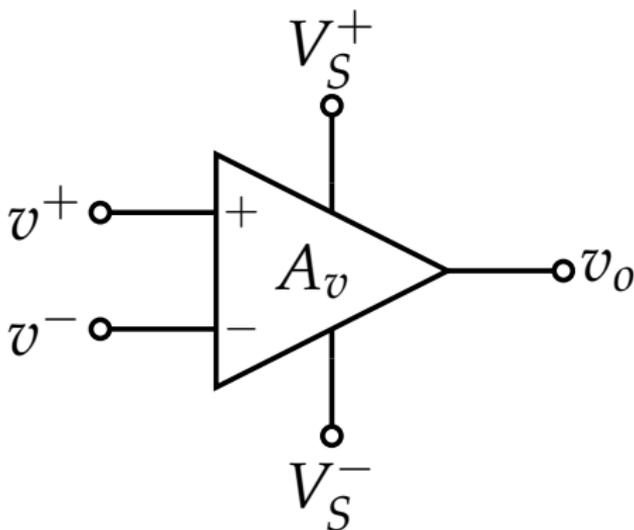
- V_S^+ and V_S^- are the power supplies. They are often not included on circuit diagrams but *must* be connected in the real circuit. v_o cannot go outside the range $V_S^+ > v_o > V_S^-$
- v^+ is called the "non-inverting" input. It is identified by a "+" next to the input line, inside the opamp triangle.
- v^- is called the "inverting" input. It is identified by a "-".
- The output, v_o, comes from the point of the amplifier symbol.
- A_v is the voltage gain (equivalent to G) which relates the output and input by the opamp equation,

$$v_o = A_v \cdot \left(v^+ - v^- \right) \tag{12}$$

A_v operates on the difference between v^+ and v^- to produce v_o.

Review

- Looked at feedback for signals and for DC (quiescent) conditions in a one transistor amplifier with and without emitter decoupling

- The situation where $R_L = R_E$ is called a "phase splitter".

- Looked at the small signal equivalent circuit of a BJT in terms of a one transistor amplifier

- Gave an example of a performance evaluation

- Noted that the value of the small signal circuit is to show which device and circuit affect the gain, not to give a numerical value (although this is possible.)

- Introduced the idea of an "analogue building block" - opamp

- presented the opamp as an implementation of a classical feedback system.

- Derived the opamp equation and presented a circuit symbol for an opamp.