Week 8: Transistor Circuits & Introduction to Feedback

Simple transistor circuits

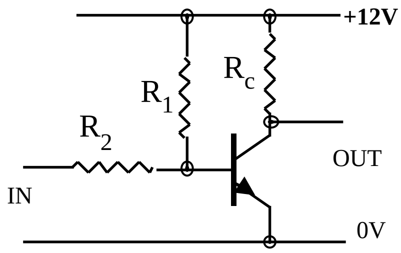
The output of most transistor circuits is taken from the collector (but sometimes the emitter). The easiest way to do this is to simply place the output transducer in series with the collector so that the collector current flows through it. This can be done for a solenoid, a lamp, a motor, a heater, ... all of which can operate with DC current.

Other transducers, such as a loudspeaker or an aerial, require an AC current so extra components are needed in order to provide this. Then there is the very common case where the output of one transistor stage is to provide the input to the following one, and so on. The components used to perform these functions are called COUPLING COMPONENTS (usually just one or two resistors and / or capacitors).

There also need to be BIAS COMPONENTS (resistors) which establish the appropriate standing currents and potentials in the circuit. Very often a given resistor will be performing both functions at once so its value has to be carefully calculated from both points of view.

8.1 Simple common emitter voltage amplifier: *signal voltage gain*

Here is the simplest functional transistor amplifier circuit. It is of the *common emitter* variety because the transistor emitter is connected to earth and is common to both the input and the output:



Here R_2 is an input coupling resistor: it serves to convert the *input signal voltage* into a variation in the base current. The term "signal voltage" means *a variation in the voltage* at any given point in the circuit. It is these variations that are amplified by the circuit and "flow" from input to output. The *signal voltage gain* is the ratio of a change in output voltage to the corresponding change in input voltage. Hence the effect of R_2 is expressed by

$$\Delta I_b \approx \Delta V_{IN} / R_2$$

[Some of this signal current actually flows into R_1, rather than the base, but if R_1 is large compared to r_b this will be relatively small. For I_c = 1 mA, β = 100, $r_b \approx$ 4 kΩ.]

R_1 is a biasing component (thought it affects the signal current slightly, as explained above). Its value is usually calculated from the required collector current: for I_c = 1 mA, β = 100, I_b = 10 µA,

$$R_1 \approx (12–0.6) / 10 = 1.14\ \text{M}\Omega.$$

Choose 1.2 MΩ as the nearest standard value.

We usually want the collector voltage to have a standing value roughly half way between the two power supply rails to allow the maximum signal amplitude. We therefore want:

$$R_c \approx (12–6) / 1.0 = 6\,\text{k}\Omega.$$

Choose 5.6 kΩ as the nearest standard value.

The output signal voltage is then

$$\Delta V_{OUT} = -R_c \Delta I_c$$

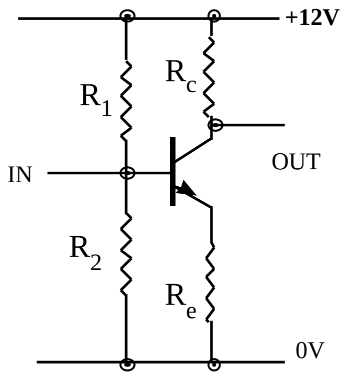
and since $\Delta I_c = \beta\, \Delta I_b$ we can find the signal voltage gain, $\Delta V_{OUT} / \Delta V_{IN}$, using the above equations.

Note that there are a few unsatisfactory features of this simple circuit and we will be progressively improving on it until we arrive at the final form in 8.5.3

Exercise 8.1
For the above circuit with the given resistor values, by calculation and experiment find the *signal voltage gain* when R_2 = 10 kΩ.
Find by calculation the minimum and maximum values of β for which the circuit will still operate as an amplifier (i.e. function *and* have a signal gain greater than 1).
Find by calculation and experiment the most positive and most negative input voltage for which the circuit will still operate as an amplifier when β=100.

8.2 Improved common emitter voltage amplifier

The main problem with the above circuit is that the bias conditions depend critically on the value of β which can vary widely between one transistor and another, even of the same type. Here is how we can establish a value for the collector current which is largely independent of the exact value of β:



Now $V_e \approx V_b - 0.6$, and $I_e = V_e / R_e$, so that establishing a constant known value for the base voltage fixes the emitter current. The potential divider R_1 / R_2 does this.

Exercise 8.2
In the above circuit, if we require I_e = 1 mA, V_e = 1.0V, R_2 = 10kΩ, find the correct values for R_e and R_1.

So why now does β matter at all? Because if it is too small the base will draw a current comparable to that flowing through the potential divider and spoil the intended bias conditions.

Exercise 8.3
Check that in this circuit the current flowing in the potential divider is much larger than the base current for β=100.
How small would β be for the base current to become comparable to the current in the potential divider?

8.3 Notation: signal current and signal voltage

We need a convenient notation to symbolise the *variation* in a current or voltage—called the *signal current* (or voltage)—as opposed to the absolute value. The most usual way is to use lower case letters for a signal current and upper case letters for the absolute value (or average value). Beards uses the exact opposite of this convention!

I will use upper case characters for the absolute value, and the Δ symbol to signify a variation from the mean value where this distinction is required. This is unambiguous and allows us to reserve lower case characters for *internal* quantities such as slope resistance and so on.

So I_c means the actual current flowing into the collector and ΔI_c means a variation from the mean value of that current in response to some input signal.

8.4 Decibels

In section 8.1 we considered the *small signal voltage gain* of a circuit. This is the ratio of the change in the output voltage to the change in the input voltage, assuming that these changes are small enough to use a linear relationship between input and output.

It is very common to need to quote a ratio of the amplitudes of two signals in this way. Sometimes the ratio is a very large or very small number; sometimes it is an awkward value such as $\frac{1}{\sqrt{2}}$; and sometimes we need to multiply these ratios together which may be a tricky piece of mental arithmetic. This is all made easier by quoting such ratios as their logarithms using a unit called the bel or decibel (B or dB), which of course is dimensionless, just as the signal ratio is dimensionless.

The bel is defined for a ratio of *power*:

The ratio of power P_1 to power P_2 is $\log_{10}\left(\frac{P_1}{P_2}\right)$ [B] $=$ $10\log_{10}\left(\frac{P_1}{P_2}\right)$ [dB].

This is extended to cover ratios of voltages and currents by quoting the power ratio that *would* result *if* the two voltages or two currents related to load resistances of the same magnitudes, even when they actually do not!

Since $P = V^2/R = I^2R$, we find:

the ratio of voltage V_1 to voltage V_2 is $10\log_{10}\left(\frac{V_1^2/R}{V_2^2/R}\right)$ [dB] $=$ $20\log_{10}\left(\frac{V_1}{V_2}\right)$ [dB],

the ratio of current I_1 to current I_2 is $10\log_{10}\left(\frac{I_1^2R}{I_2^2R}\right)$ [dB] $=$ $20\log_{10}\left(\frac{I_1}{I_2}\right)$ [dB].

Note that if V_1 is smaller than V_2 then the ratio is a negative number in dB.

Here are some typical examples:

P_1/P_2	V_1/V_2 or I_1/I_2	ratio in dB
1	1	0
2	$\sqrt{2}$	+3
4	2	+6
10	$\sqrt{10}$	+10
100	10	+20
10^{10}	10^5	+100
1 / 2	$1/\sqrt{2}$	–3
1 / 4	1 / 2	–6
1 / 10	$1/\sqrt{10}$	–10
1 / 100	1 / 10	–20
10^{-10}	10^{-5}	–100

8.5 Coupling a multi-stage transistor circuit

In the example of a single-stage transistor amplifier given in section 8.2 the base voltage was about 1.6V and the collector voltage was about 6V for a supply voltage of 12V. If the output of this circuit were connected directly to the input of a similar succeeding stage then the base of the transistor in that stage would have to be at 6V. Since its collector voltage must be greater than the base voltage but less than the supply voltage, it would need to be something like 9V. Directly coupling this to a third stage would require the third transistor to have a collector operating at about 10.5V, and so on, with the collector voltages progressively approaching the supply voltage as we add more and more stages.

Such a scheme is actually unworkable for more than two or three stages because Ohm's Law dictates that the collector resistors and / or the collector currents would have to be made progressively smaller, which defeats the object of making an *amplifier*. This is because the voltage gain of each stage is proportional to the value of the collector resistor and the maximum signal amplitude is proportional to the voltage drop across the collector resistor.

Using alternating n-p-n and p-n-p transistor stages is one way to improve matters. Another is to insert Zener diodes between each collector and the following base to produce a fixed difference in potential between them. Even then, there is the problem that a small error in establishing the correct bias conditions of the first stage gets amplified up to a very large error in the last stage and the circuit may well not work at all.

We see then that the problem of designing a high-gain “DC” amplifier is a very difficult one using discrete components. The operational amplifier comes to our rescue in the end, though (next week).

However, in the common case where it is not required to amplify signals of a frequency less than some particular value, the straightforward answer is to use *AC coupling*. The amplifier is then called an *AC amplifier*.

8.5.1 AC coupled transistor amplifier

This is simply achieved by connecting the output of one stage to the input of the next using a *capacitor*.

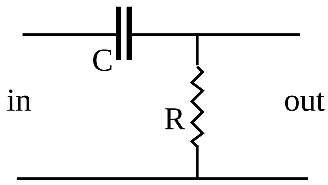
At high frequency the impedance of this coupling capacitor is small so the *signal voltage* is passed on essentially unaffected.

The capacitor cannot pass a continuous DC current, however, so the bias conditions of one stage can be established entirely independently of those of its neighbours.

The value of the capacitor should be chosen to be large enough not to cause the signal to be attenuated at the lowest desired signal frequency. This is usually specified with respect to the "3dB roll-off frequency" which is the frequency where the impedance of the capacitor equals the net resistance in series with it. [Note: the larger the value of a capacitor the larger are its dimensions and the more expensive it is, so we make capacitors as small as we can for their required purpose.] We can illustrate this for the "single pole high-pass filter".

8.5.2 Single pole RC high-pass filter

This is a potential divider composed of a resistor and a capacitor.



The reactance of the capacitor is $X = 1/(2\pi f C)$, and the combined impedance is

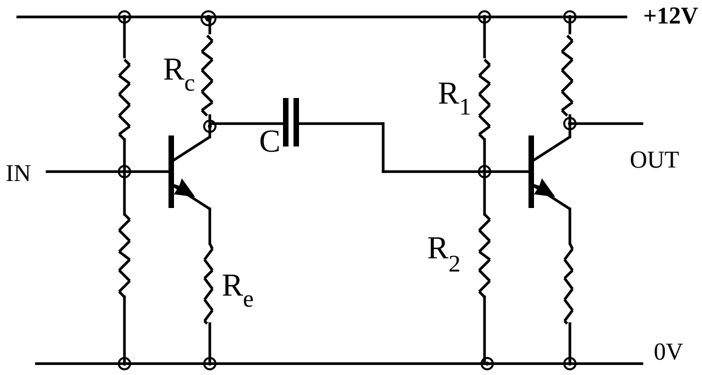
$$Z = \sqrt{R^2 + X^2}.$$

The ratio V_o / V_i is R/Z, which when $X = R$ is $1/\sqrt{2}$ or –3dB.

This occurs at the frequency $f_o = \dfrac{1}{2\pi RC}$.

At frequencies less than this, $Z \approx X$, so the attenuation is $R/X = 2\pi fRC = f/f_o$. This means that the output halves for each halving of the frequency. The attenuation is then said to be "6dB per octave".

8.5.3 A typical AC coupled transistor circuit



What is the effective resistance in series with C in this circuit? It is R_c plus the parallel combination of R_1 and R_2, if we assume that the internal resistance r_c is much larger than R_c and r_b is much larger than R_1 or R_2. (Think of the current flow from one fixed potential point at the top of R_c, through C, to the other fixed potential points at the top of R_1 and the bottom of R_2.) In most circuits R_c will be much smaller than R_1 or R_2 so it can be neglected for the calculation of C (the current in a collector circuit is typically 100 times the current in a base circuit, so the resistances are also typically 100 times smaller). The parallel combination of R_1 and R_2 will be approximately equal to whichever is the smaller of the two (usually R_2), so since we only need a rough estimate of the *minimum* value to chose for C, the calculation is not that difficult in practice.

Exercise 8.4
In the above circuit, if $R_c = 10\,\text{k}\Omega$, $R_2 = 820\,\text{k}\Omega$, and $R_1 = 2.2\,\text{M}\Omega$, find the approximate minimum value of C such that the amplifier gain will be maintained down to a frequency of 50 Hz. Check your result with *Crocodile Clips* using an oscillator source and the oscilloscope feature. (Remember the Norton and Thévenin theorems!).

8.6 Introduction to negative feedback

Consider the circuit of section 8.2, or the first stage of the circuit above. We can tell "by inspection" that the signal voltage gain is very close to R_c / R_e. This is because the collector current is almost equal to the emitter current: the ratio is in fact $\beta / (1+\beta)$. Hence the ratio of voltages across these resistors is equal to the ratio of resistances. Also the emitter signal voltage is almost equal to the input signal voltage on the base because the base-emitter voltage is essentially a constant. So finally the ratio of the voltage across the collector resistor to the base voltage is the ratio of collector resistance to emitter resistance. The signal voltage gain is the ratio of *changes* in output and input voltages, hence this too is approximately equal to the ratio of collector resistance to emitter resistance. To be more exact we should also count the "internal" emitter resistance, r_e as part of "R_e" as well as the external component.

How is it that the voltage gain depends almost entirely on the values of two resistors, and hardly at all on the current gain of the transistor (β)? This result is typical of a *negative feedback circuit*, which this one is an example of, and it relies on the fact that we were able to assume that the current gain β is large, or equivalently that the base-emitter signal voltage is very small.

Here is how we can understand the operation of *negative feedback* in this circuit. The basic amplifying element in this circuit is the transistor and the input to this element is applied at the base-emitter connections. The output terminal is the collector. The input voltage applied to the transistor is the input voltage to the *circuit* minus the voltage at the emitter. The voltage at the emitter is proportional to the output voltage, as we saw above, so a fixed fraction of the output voltage is being subtracted from the input to the circuit before being applied to the amplifying element. Hence the name "negative feedback".

In a negative feedback circuit, provided the amplifying element has a large gain, we can treat the circuit as though the input to the amplifying element is negligibly small compared to the input to the circuit. In the present case this means taking the base-emitter *signal* voltage to be negligibly small (or equivalently, the absolute base-emitter voltage to be *constant*) and this was the argument we used above in deducing the voltage gain. We will take a more rigorous look at negative feedback next week.

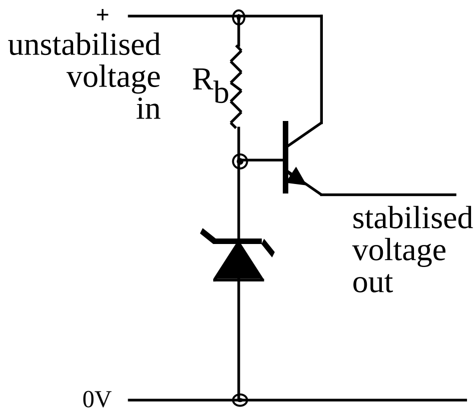
Exercise 8.5
For the circuit of section 8.2, use *Crocodile Clips* to find the actual voltage gain at 1000 Hz when R_e = 200 Ω and R_c = 6 kΩ, and compare this with the rule-of-thumb calculation. (Use R_2 = 10 kΩ and adjust R_1 to give a collector current of 1 mA.)
Increase R_e to 600 Ω keeping R_c and the collector current the same and again compare the actual gain with the rule-of-thumb. Is it possible to achieve a voltage gain as high as β (= 100) ?

8.7 The common collector circuit ("emitter follower") and the power voltage stabiliser

In the above circuit if we were to take the output from the emitter instead of the collector then we would have a *unity-gain amplifier*. The collector resistor would then serve no purpose and could be replaced by a direct link from the collector to the power supply. This form of unity gain amplifier is known as the common collector transistor amplifier (otherwise known as the "emitter follower").

Although there is no actual voltage gain (in fact the voltage gain is slightly less than 1 – can you see why?) there is a power gain because a much larger signal current can be drawn from the emitter than is input at the base. The headphone output of a CD player is often provided by means of a common collector transistor circuit.

A development of this is the power voltage stabiliser where the input to the common collector circuit is a Zener diode stabiliser. The amount of current that can be drawn from this stabiliser is now (1+β) times the current that can be drawn from the Zener diode circuit alone.

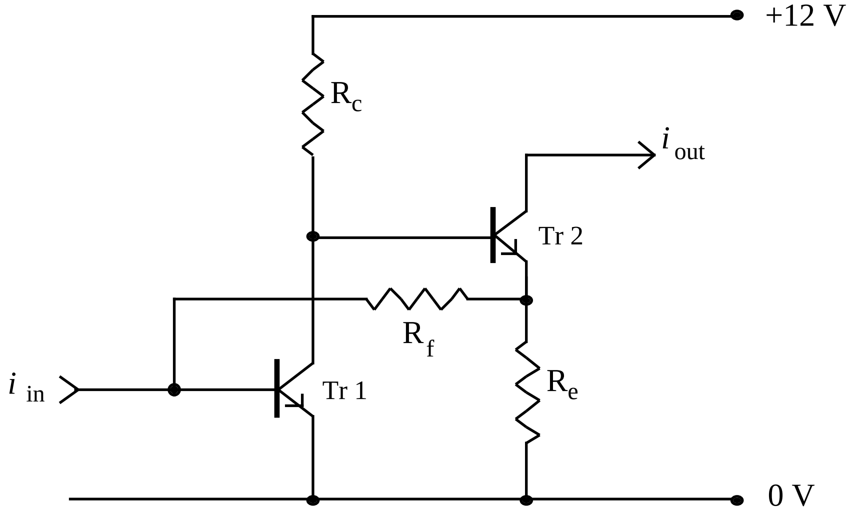


Exercise 8.6
Design and construct in Crocodile Clips a power voltage stabiliser that will produce an output of 12V and work with an input between 15V and 25V.
Connect a load resistance to draw 100 mA and make measurements to find the output slope resistance and the voltage gain, expressing the latter in dB.
Compare this slope resistance with the rule-of-thumb value: $r_e \approx 40/I_e$.
Compare the voltage gain with the rule-of-thumb value r_Z / R_b, where r_z is the Zener diode slope resistance.

8.8 Current feedback

The negative feedback of the circuits above was described in terms of *voltages*, and this resulted in circuits with well defined voltage gain. We can also use *current feedback* where a current proportional to the output current is subtracted from the input current before being applied to the amplifying element.

Here is an example.



The output current passes through R_e generating a voltage proportional to the output current. Through R_f this voltage then causes a current to be subtracted from the input current at the base of the first transistor: the feedback current. This feedback current is proportional to the output current and is of the opposite polarity to the input current so we have a negative feedback circuit.

Assuming the gains of the transistors are large we can then say approximately

$$\Delta I_{in} + \Delta I_f \approx 0$$

$$\Delta I_{in} \approx -\Delta I_f \approx -\frac{\Delta V_e}{R_f} = -\frac{R_e\ \Delta I_{out}}{R_f}$$

$$\text{current gain } = \frac{\Delta I_{out}}{\Delta I_{in}} \approx -\frac{R_f}{R_e}.$$

Exercise 8.7 Using Crocodile Clips construct the above circuit for $R_e = 400\,\Omega$ and $R_f = 40\,k\Omega$, choosing a value for R_c which will give an average output current of 5 mA (I_{in} =0). Make measurements to find the current gain and compare with the rule-of-thumb value. Change R_f to $400\,k\Omega$, and repeat the above exercises.

8.9 Designing the Common Emitter Amplifier

The most systematic procedure to adopt when designing a common emitter amplifier with emitter feedback is as follows.

1. Choose the supply voltage. This is not critical and normally anything in the range of about 6 V to 20 V will do unless a particularly high output voltage amplitude is required (when a special high voltage transistor must be used). However if a large voltage gain is required then the circuit will be more stable with temperature changes when a higher supply voltage is used since this will give a higher emitter voltage (see 6).

2. Choose the average collector current. This also is not critical unless a high output power is needed and usually any value in the range 0.1 mA to 10 mA will be satisfactory.

3. Choose the mean collector voltage, normally a bit more than one half of the supply voltage in order to provide for the greatest possible output amplitude.

4. Determine the value of the collector resistor from the above constraints.

5. Determine the value of the emitter resistor to give the required voltage gain, remembering to take account of r_e. Do not try to achieve a voltage gain larger than $\beta / 2$ otherwise the emitter voltage will be too small for stability (again see 6).

6. Calculate the mean emitter voltage and hence the mean base voltage. The mean emitter voltage should be at least 0.5 V (i.e. $\geq V_{be}$) in order that the bias conditions are stable against temperature variations etc.

7. If the β of the transistor is known, calculate the mean base current. Otherwise assume a β of 100.

8. Calculate values for the base bias potential divider resistors so that they pass a current several times greater than the mean base current and provide the required mean base voltage. This will provide stable bias conditions and also usually mean that the input impedance of the circuit is dominated by these resistors so that the effect of the transistor can be neglected in this respect.

9. If AC coupling is to be used, calculate the input coupling capacitor so that the voltage gain will be maintained down to the lowest required signal frequency. The value of the output coupling capacitor will depend on the load or the input resistance of the following stage of amplification.

10. Since some approximations were probably made in arriving at these component values you could now “construct” the circuit in *Crocodile Clips* and trim the values to give the precise behaviour required.

Exercise 8.8

Design a single transistor common-emitter AC amplifier to the following specifications:

β of transistor = 100,
Supply voltage = 15 V,
Average collector current = 4 mA,
Voltage gain = 10,
Low frequency roll-off = 40 Hz (3 octaves below middle E; base guitar's lowest frequency).

Test the circuit using Crocodile Clips and adjust the values of the components if necessary to achieve the precise specifications.