Week 7: Discrete Analogue Components

Note: Throughout this section of the course, unless stated otherwise, all exercises are to be done using *Crocodile Clips.*

7.1 Transducers: the need for analogue circuits

Electronic equipment is of no value unless it connects with the outside world. Some external process needs to be converted into an electrical “signal”, which is then applied to the electronic circuit. The output of the circuit also needs to be converted into some form that can have an effect on the external environment. Devices that perform these operations are called TRANSDUCERS.

Examples of transducers

DEVICE	IN/OUT	PHYSICAL PROPERTY
Microphone	INPUT	sound pressure wave
Switch	INPUT	binary mechanical movement
Potentiometer	INPUT	mechanical rotation
Thermocouple	INPUT	temperature of heat source
Light-dependent resistor	INPUT	intensity of light
Geiger counter	INPUT	ionising radiation
TV camera tube	INPUT	light intensity pattern
Loudspeaker	OUTPUT	sound pressure wave
Solenoid	OUTPUT	binary mechanical movement
Motor	OUTPUT	mechanical rotation
Ohmic heating element	OUTPUT	heat
Lamp	OUTPUT	intensity of light
Particle accelerator	OUTPUT	high energy particle beam
TV screen	OUTPUT	light intensity pattern
Aerial	INPUT *or* OUTPUT	Electromagnetic radio wave

All of these transducers, except the switch and the solenoid, produce or respond to a continuously varying voltage or current. They cannot therefore be connected directly to a digital circuit. Circuits that handle such continuously varying signals are called ANALOGUE CIRCUITS. Even the switch and the solenoid cannot be connected directly to logic gates and require some kind of intermediate circuitry of the analogue type: they must be "matched" to the standard voltage and current levels of digital circuits.

The most important of all analogue circuits is the AMPLIFIER which will boost the power of the signal from an input transducer – without significantly distorting its form – up to the level needed to drive an output transducer. There may be some digital processing of the signal along the way, but very often all the signal processing can be achieved more easily using only analogue techniques.

Examples of complete electronic systems

Purely analogue:

- ♦ Simple AM/FM radio
- ♦ Simple TV
- ♦ Record player
- ♦ Audio cassette player (with or without Dolby noise reduction)
- ♦ Light dimmer
- ♦ Electric cooker
- ♦ Guitar amplifier
- ♦ Basic oscilloscope
- ♦ Oscillator

Analogue signal processing with digital control circuits:

- ♦ Video recorder
- ♦ Car ignition circuit
- ♦ Theatre lighting control
- ♦ Telephone exchange
- ♦ Radio or TV with advanced features

Analogue amplifiers with digital signal processing:

- ♦ CD or DVD player
- ♦ Computer
- ♦ Printer
- ♦ Electronic echo chamber
- ♦ Storage oscilloscope
- ♦ Digital multimeter

7.2 Devices used in analogue circuits

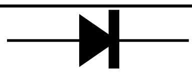
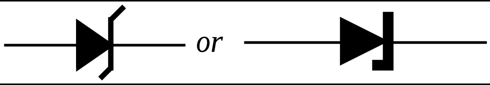
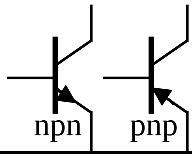
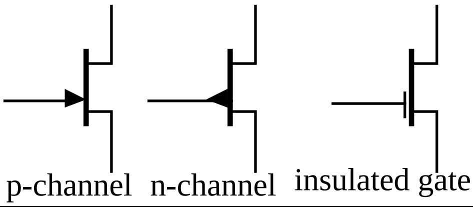
Commonly used complex analogue circuits are packaged into INTEGRATED CIRCUITS which look very like the integrated circuits used in digital electronics. The ones most commonly encountered are:

the operational amplifier,
the comparator,
the timer,
the voltage regulator.

These will be covered in two weeks' time.

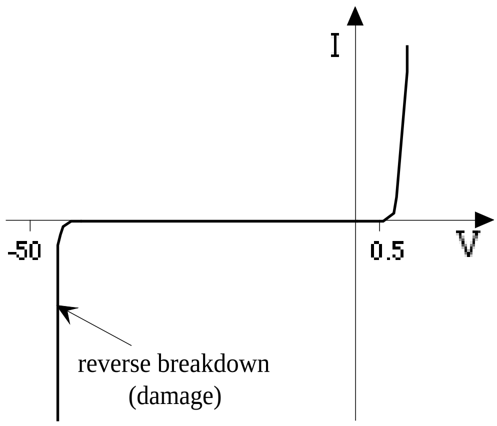
Because of the extremely wide range of types of analogue circuit, most simple ones are not available in integrated circuit form and must be constructed from DISCRETE COMPONENTS.

Apart from the familiar resistor, capacitor and inductor, these are the following:

Diode		allows current to pass in one direction only
Zener diode		establishes a constant known voltage
Bipolar junction transistor		amplifies a signal current
Field effect transistor (FET)		amplifies a signal voltage; voltage-controlled switch.

7.3 The diode

Here is the semiconductor junction diode's *characteristic*:



The forward part of the characteristic can be closely modelled by the equation

$$I = A\mathrm{e}^{BV}.$$

This is not quite correct since it does not pass through the origin, but usually the parameter A is so minute that the expression is very close to the actual behaviour for all practical purposes.

It is interesting to find the *slope resistance*:

$$\frac{\mathrm{d}I}{\mathrm{d}V} = BA\mathrm{e}^{BV} = BI$$

$$r = \frac{\mathrm{d}V}{\mathrm{d}I} = \frac{1}{BI} \approx \frac{0.04}{I} = \frac{40}{I[\mathrm{mA}]}\Omega.$$

The parameter $1/B$ is theoretically kT/e which at room temperature is about 0.025 V $= \frac{1}{40}$ V. In practice B is less than 40 V^{-1} by up to a fact or of 2, so r may be up to $50/I[\mathrm{mA}]\ \Omega$.

This relation will be useful when we come to the bipolar junction transistor. For most practical purposes when using the diode we can use the simple approximation that the forward voltage is about 0.6 V: this is a good enough approximation for most silicon based diodes for normal current values (up to 1 amp or so).

When a voltage is applied across a diode in the reverse direction a negligible current flows, up to the point where the diode breaks down. Reaching this point will usually cause irreversible damage to the diode. It is also possible to damage a diode when biassed in the forward direction by passing too high a current.

The important parameters for a diode, therefore, are:

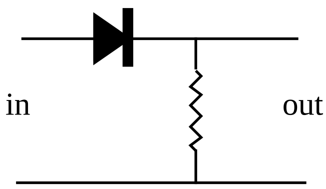
Diode Parameters:

Forward voltage drop	~0.6V universal
Maximum forward current	select according to application
Maximum reverse voltage	select according to application

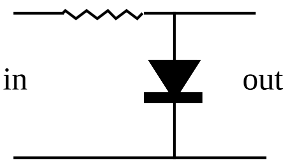
7.4 Simple circuits using diodes

A diode should always have a resistor of some kind in series with it, otherwise there is a high probability that the maximum forward current will be exceeded.

One diode and a resistor connected as a potential divider makes a *rectifier*. There are two ways to do this:



$$V_{out} = V_{in} - 0.6, \text{ if } V_{in} \text{ positive;}$$
$$V_{out} = 0, \text{ if } V_{in} \text{ negative.}$$

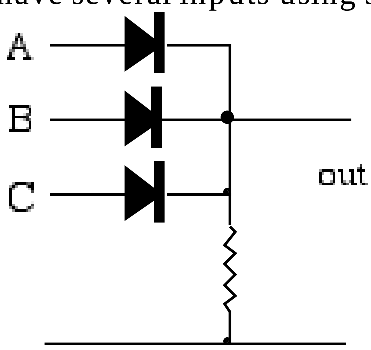


$$V_{out} = 0.6, \text{ if } V_{in} \text{ positive;}$$
$$V_{out} = V_{in}, \text{ if } V_{in} \text{ negative.}$$

The first version is the one most commonly used since it transfers nearly all the input power into the load with little voltage drop when the diode is forward biassed. The second version would probably result in a significant voltage drop across the resistor when any substantial current flows into the output circuit.

Exercise 7.1:
In *Crocodile Clips*, use the above circuits, together with a variable voltage supply, a voltmeter, and an ammeter, to demonstrate roughly the diode's forward and reverse characteristics.

We can develop this circuit to have several inputs using several diodes:

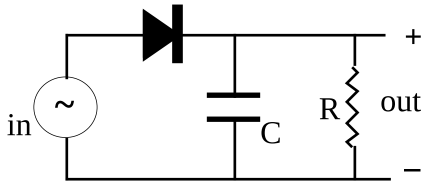


$$V_{out} = \text{MAX}(V_A, V_B, V_C) - 0.6, \text{ for positive inputs}$$

This is the principle of the positive logic diode OR gate.

Exercise 7.2:
Demonstrate that the above circuit functions as a positive logic OR gate.
Construct a 3-input positive logic diode AND gate. [Hint: you will need a positive supply voltage – say 5V – to make this circuit. Also: remember de Morgan.]
How would you write the analogue equation of this circuit?

The smoothed power half-wave rectifier is used to convert an AC power source such as a transformer output into a roughly constant DC power source:

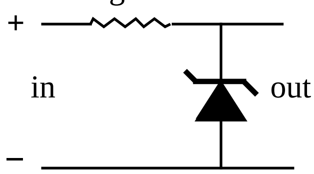


On positive half-cycles of the input, when V_{IN} exceeds V_{OUT}+0.6, the capacitor charges up through the diode. For the remainder of the positive and all the negative half-cycles the capacitor discharges into the load, *R*.

Exercise 7.3:
Use an oscilloscope probe to investigate the form of the output of the smoothed rectifier for various values of *R* and *C*.
Try to obtain the maximum output power with the most constant voltage and also observe conditions where the output exhibits significant "ripple".
Explain on a timing diagram why the ripple has the form that it does.

7.5 The Zener diode

The Zener diode is similar to an ordinary junction diode but is designed so as not to suffer damage when operated in its reverse breakdown region provided the power dissipated is not allowed to exceed the rated maximum. The reverse breakdown region of its characteristic has a very small slope resistance so in combination with a suitable resistor we can produce a constant voltage source.



The important parameters of a Zener diode are:

Zener Diode Parameters:

Reverse breakdown voltage	select the desired constant voltage
Reverse breakdown slope resistance	hopefully small enough for the application
Maximum power	select to be greater than (breakdown voltage) × (current to be supplied to load)

7.5.1 Load lines

The Zener diode circuit shown above provides a good illustration of the analytical technique called a *load line*. This means superimposing the characteristics of the diode (or other component) with that of its bias resistor (the “load”) on the same graph in order to analyse the operation of the circuit in a graphical way.

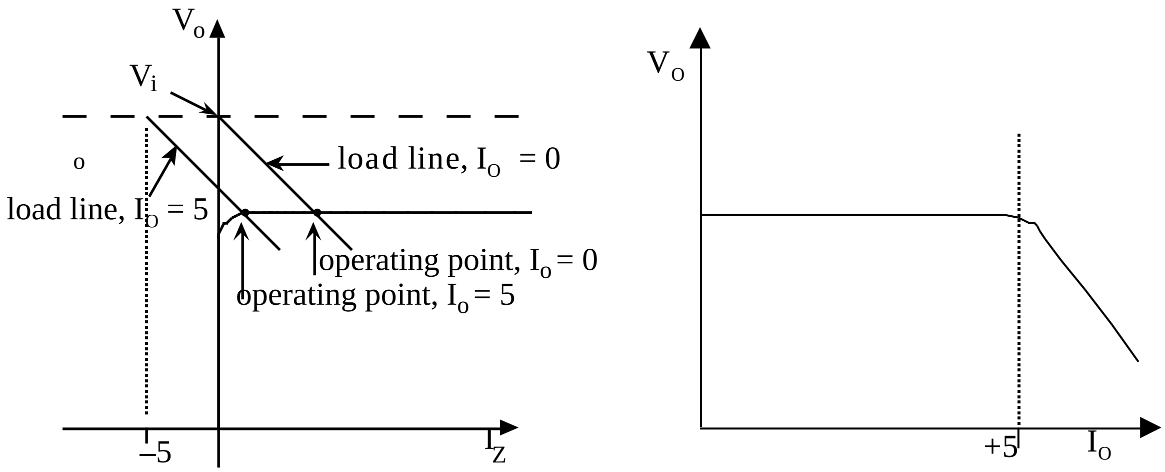
If the current flowing in the diode is I_Z, the current flowing out of the circuit is I_o, and I is the current flowing in the bias resistor, then

$$I = I_Z + I_o$$

$$V_i - V_o = RI = R(I_Z + I_o)$$

$$V_o = V_i - RI_o - RI_Z \ .$$

Superimposing this straight line equation on the diode characteristic we have



We then see that the maximum current that can be drawn from the stabiliser circuit is approximately equal to the current flowing in the diode with zero output current. The current in the bias resistor is almost constant since the potentials at its terminals are almost constant.

Here, the Zener diode is acting as a “constant voltage source”. The load line type of analysis can also be applied to constant current sources, such as the collector of a transistor.

Exercise 7.4:
In *Crocodile Clips* construct a constant voltage circuit using a Zener diode.
Include a variable voltage supply and a load resistor and a voltmeter and ammeter to measure the output into the load.
Choose the diode bias resistor to be 100 times the diode's slope resistance.
Investigate the effect of varying the supply voltage and the load resistance.

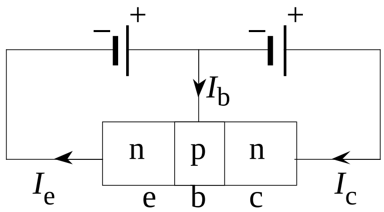
7.6 The bipolar junction transistor

Transistors are three-terminal devices so their characteristics cannot be simply presented on a single graph as can be done for the diode. Each characteristic graph shows one parameter plotted against a second whilst a third is held constant. With three potential differences and three currents this gives around 60 possible characteristic graphs! Hence the very intimidating *hybrid parameter model* with its many “h” parameters as used in Beards and most other academic electronics textbooks.

In the early days of transistor technology it could be argued that this sledge-hammer formal approach was necessary because the devices then available had very poor performance and circuits needed to be fully optimised to get the most out of them. However these day virtually all silicon technology junction transistors come very close to the "ideal" transistor, so the practical task of designing circuits is much simpler and, provided that sensible rules of thumb are followed, we only need to know the value of one or two parameters for any given transistor.

Junction transistors are made up of three layers of semiconducting material of alternating type: either "n-p-n" or "p-n-p", each layer having an external connection or "terminal". N-type semiconductor material has a surplus of negative charge-carriers (electrons) and p-type material has a surplus of positive carriers, called *holes*. The middle layer is very thin and is called the "base": a relatively small current flows into the base from the external circuit. The outer two layers are called the "emitter" and the "collector", the collector being somewhat thicker than the emitter and having a smaller current-carrier density (determined by the concentration of chemical "doping"). Most of the current flowing in a transistor passes between the collector and the emitter, crossing the thin base layer on the way. The generic name for this kind of transistor derives from the fact that it consists of two p-n junctions: the emitter-base junction, and the base-collector junction.

Let's focus on the n-p-n type which contains an n-type emitter, a p-type base, and an n-type collector. This is how, conceptually, the three terminals must be biassed for the transistor to work as required – as a current amplifier:

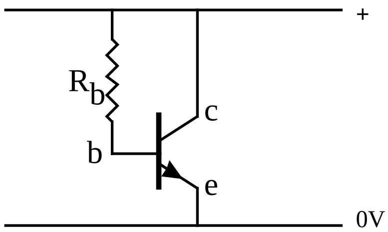


A single isolated p-n junction forms a diode which will only pass current in one direction: when the "p" electrode is positive with respect to the "n" electrode. It is then said to be *forward biased*. If the polarities are reversed, the junction is *reverse biased* and a negligible current then flows through the diode.

In a transistor however we have *two junctions* in very close proximity, when the behaviour of the *reverse* biased junction (b-c) is substantially modified from the diode characteristic if the *other* junction (e-b) is *forward* biased.

Transistors are designed to normally operate with
the emitter-base junction forward biased, and
the base-collector junction reverse biased.
Hence the polarities should be as shown in the diagram above. For a p-n-p type the opposite polarities are used.

In practice the base-emitter junction must have a resistance in series with it so as to limit the current since it is acting as a forward biassed diode. The minimum circuit, then, to properly bias an n-p-n transistor using a single power supply is:



Exercise 7.5:
With *Crocodile Clips* construct the above circuit using a variable resistor for R_b and a power supply of 12V. Equip your circuit with voltmeters and ammeters so as to observe the behaviour as R_b is varied.
Make rough graphs of V_{be} vs I_b and I_c vs I_b .
Note the point at which the transistor is destroyed!

The proportionality between the collector current and the base current is usually described by the parameter β:

$$I_c = \beta\, I_b,$$

where β for any particular transistor would typically have a value of a few hundred.

I_c and I_b both flow in the same direction, into the emitter, so the emitter current is just a fraction of a percent larger than the collector current and can be considered equal to it for most practical purposes.

A “perfect” transistor would have a constant value for β regardless of what voltage is applied across the base-collector junction and regardless of the magnitude of the currents flowing through it. The collector would then form a perfect current source. In practice β does depend slightly on the voltages and currents of the circuit and also on the temperature of the transistor, but this is usually not important for the correct operation of the circuit.

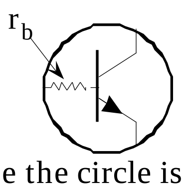
A properly designed transistor circuit does not depend critically on the precise value of β.

It’s useful to think in terms of the *ideal transistor* which would have constant β and would also have zero base-emitter voltage, or a small and constant value. We come close to this by approximating V_{be} to 0.6V, as for a forward biassed diode.

The diode characteristic of the base-emitter junction is the principle source of non-linearity in the transistor's behaviour. This can be a nuisance in designing circuits, but we have the simple rule for calculating the slope resistance of this junction:

$$r_b \approx \frac{40}{I_b[\text{mA}]}\Omega.$$

Our working model for a practical transistor therefore could look like this

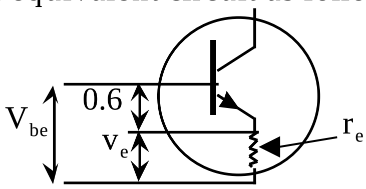


where the transistor symbolised inside the circle is regarded as *ideal*.

One further step takes us to the model that we will finally be using. Practical circuit designs invariably require I_e (and I_c) to be determined by resistor values, and the exact value of I_b is more or less accidental, depending on the value of β, and not at all critical. It is therefore better to have a model that does not require an exact knowledge of I_b. This is easily achieved, as follows.

$$\begin{aligned} r_b &= \frac{dV_{be}}{dI_b} \approx \frac{40}{I_b[\text{mA}]} \\ &= (1+\beta)\frac{40}{I_e[\text{mA}]} \quad (\text{since } I_e = (1+\beta)I_b) \\ &\approx (1+\beta)\frac{dV_{be}}{dI_e} \quad (\text{again, since } I_e = (1+\beta)I_b \text{ and } \beta \approx \text{const.}) \\ &\equiv (1+\beta)r_e \end{aligned}$$

where we have defined an *effective internal emitter resistance,* $r_e = \frac{dV_{be}}{dI_e} \approx \frac{40}{I_e[\text{mA}]}$. This definition translates into an equivalent circuit as follows:



We see that $\Delta V_{be} = \Delta v_e$, the fictional “internal” emitter voltage. (Note the small letters used for internal parameters, to distinguish from external values.) Hence

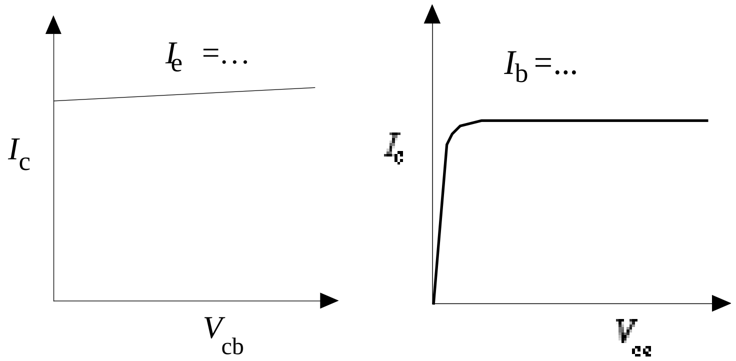
$$r_b = (1+\beta)\frac{dV_{be}}{dI_e} = (1+\beta)\frac{dv_e}{dI_e} = (1+\beta)r_e$$

as required, and

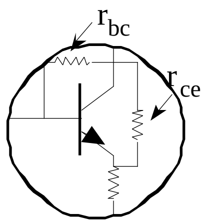
$$r_e \approx \frac{40}{I_e[\text{mA}]}\,\Omega.$$

Note: r_b or r_e are *alternative* ways to represent the base-emitter characteristic. They must not both be used together.

If we look at typical collector-emitter characteristics we see that the collector current is almost independent of the collector voltage:



The slopes in the above graphs are very much exaggerated. If we wished to extend our model to take account of these effects we would add in effective internal e-c and b-c resistances:



r_{ce} would typically be very large (> 1MΩ), and r_{bc} is typically extremely large (> 100MΩ). This means that provided we keep all external resistors to within a certain range (<< 1MΩ) and collector currents within a certain range, we can neglect the effects of these equivalent internal resistances.

Conditions for using the simple equivalent internal emitter resistance model:

External resistances in range 10Ω – 100kΩ,
Collector currents in range 0.1mA – 100mA.

The important transistor parameters are then

Junction transistor parameters:

current gain	β	100 – 500
internal emitter resistance	r_e	$40/I_e$, universal
maximum collector-emitter voltage	$V_{eb,MAX}$	30 – 500 V
maximum collector power dissipation	$P_{c,MAX}$	> 0.5 W

Here $P_C = V_{cb}I_c$.
Sometimes, for high power applications, we will also need to take note of the maximum allowed collector current.

It should also be noted that the base-emitter junction usually has quite a low reverse breakdown voltage of 4 or 5 volts, so reverse polarity here should if possible be avoided.

For handling signals at very high frequency (> 1MHz) it is also important to take note of the *current gain bandwidth product*, f_t. (f_t/β) is the frequency at which β starts to fall at high frequency.

For the vast majority of applications then, the only thing you need to specify is the approximate value of β required, and virtually any transistor will probably do the job!