WACL Electronics Course

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Contents

Understanding the electronics behind processes or sensors used in the field can help to optimise time, reduce costs and find tailored solutions to problems within research. Whether you are repairing equipment, designing a simple system to automate data measurement or to help explain why read data differs from whats expected.

This course will take you through the basics, while linking it to examples important for chemistry and atmospheric research. By the end of the course, you should understand basic electronics theory and practice, a knowledge of terminology used, and should be able to build a basic system using a sensor and control loop.

The course will touch upon a range of areas that are useful to be aware of when dealing with electronics, such as enclosures, environmental factors, sourcing parts and safety. For an alternate way to look at theories, there are references to chemistry theory. We will start with the basics of electronics. There are multiple ways to represent this, we will start with the physics, using analogies where helpful.

0.1 Electronics Fundamentals

Electronics involves a flow of electrons, for a transfer of energy over time (i.e. power). We represent this through voltage and current, seen as key units in electronics. If represented as letters within a mail network, voltage is the number of letters each mail person carries, where current is the rate of new batch deliveries. A component or drop-off point along the network has resistance, which is the number of letters they pick up from each mail person.

From a physics standpoint, electronics works through transferring electrical energy, which goes through a conversion process in components. A resistance causes a heat conversion/heat loss. There is also capacitance and inductance, discussed later on, due to conversion to electric and magnetic potential.

Focusing just on resistance and power, for now, we can represent this as several key physics equations, important for physics-based electronic theory and practice.

$$V = IR, P = IV, P = I^2R, P = E/T$$

It is possible to derive $P = I^2R$ by rearranging and putting $V = IR$ into $P = IV$. We can see this below-

$$V = IR \Longleftrightarrow P = IV$$

$$P = I(IR)$$

$$P = I^2R$$

Voltage is represented with V, with the unit Volt. Current is represented with I, with the unit Ampere (Amp). Resistance is represented with R, with the unit Ohm (with the Greek letter Ω). Power is represented with P, with the unit Watt. Time is represented with T in seconds.

Quiz

1. What does resistance demonstrate?

a) The rate of flow of electrons.

b) The energy in each "packet" or electron.

c) Conversion of electrical to thermal energy/ heat.

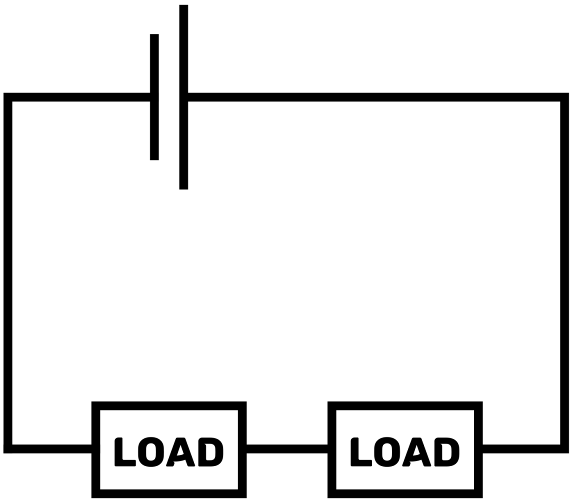
2. Demonstrate how you would go from the equation $P = I^2R$ to $P = IV$.

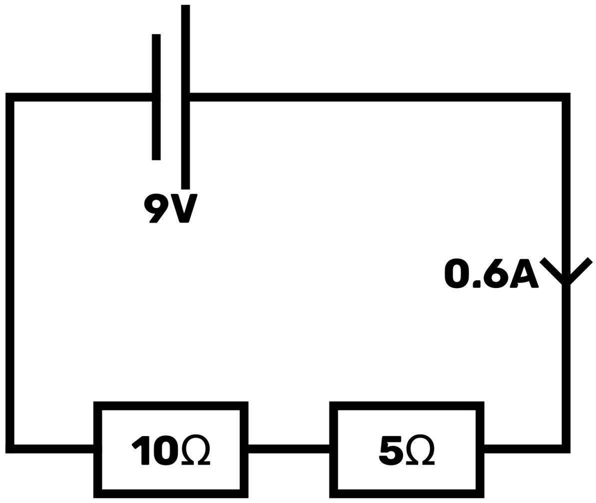
3. A circuit has a 3V battery source, with 0.5A of current flow. What is the resistance seen in the circuit, and the overall power draw.

0.1.1 Series and Parallel

You can wire a circuit with parallel and series elements. A series circuit has a single loop, with components connected one after another, sharing a single voltage. A parallel circuit can have more than one loop branching out. Each loop has a voltage equivalent to the input, with the current split between them, based on their resistance.

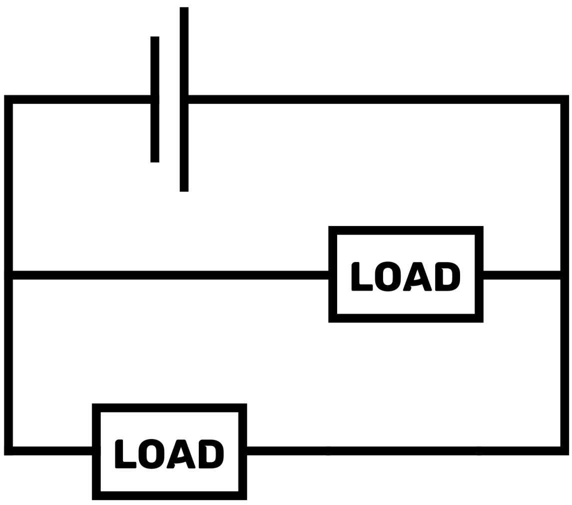
Therefore, the voltage in a series loop will be distributed based on the voltage ratios. For example, there is a 10Ωand 5Ωresistor, with a 9v supply, there would be a voltage drop of 6v through the 10 ohm resistor and a 3v drop through the 5ohm resistor. With a total resistance of 15ohm, we can calculate the current to be $V = IR$, $I = V/R$, $I = 9/15 = 0.6A$.

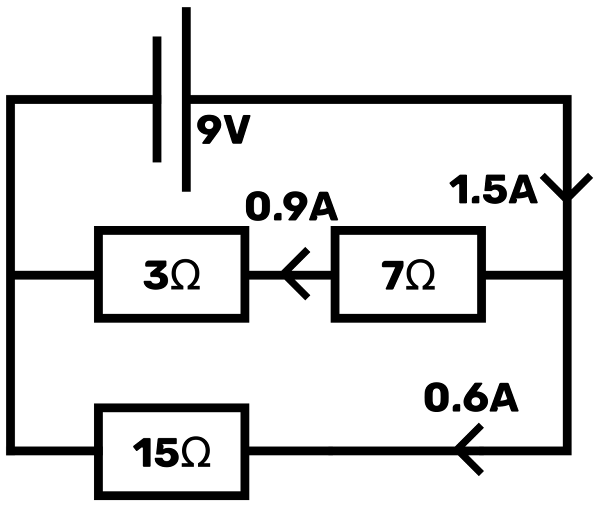




A parallel circuit has equal voltage across each path, with the current being split. Because of this, resistors in parallel have a total resistance lower than the lowest resistance path. We can calculate this using the below equation-

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$





Therefore, an example with the following circuit with 2 resistors of 3ohm and 7ohm, in parallel with a single resistor of 15ohm. You first add the series resistors, therefore R_1 is 10ohm and R_2 as 15ohm. Therefore, putting it into the equation gives us the below-

$$\frac{1}{R_{total}} = \frac{1}{10} + \frac{1}{15}$$

$$\frac{1}{R_{total}} = \frac{1}{6}$$

$$R_{total} = 6\Omega$$

Quiz

1. Which of the following statements are true?

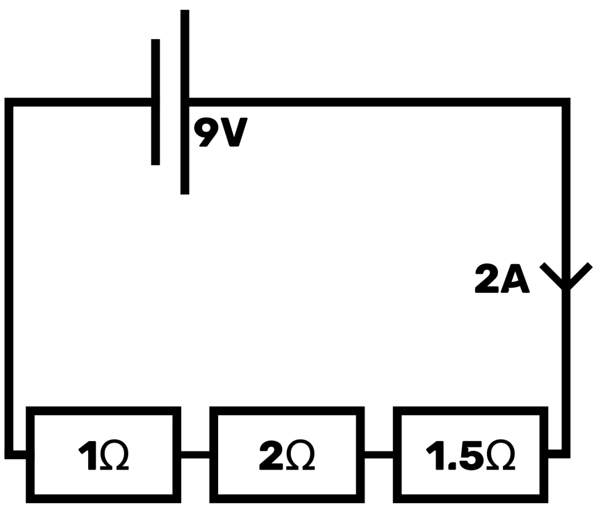
a) Current is equal down each path from a junction.

b) Current is split at a path junction, based on each paths resistance.

c) Voltage is equal down each path from a junction.

d) Voltage is split at a path junction, based on each paths resistance.

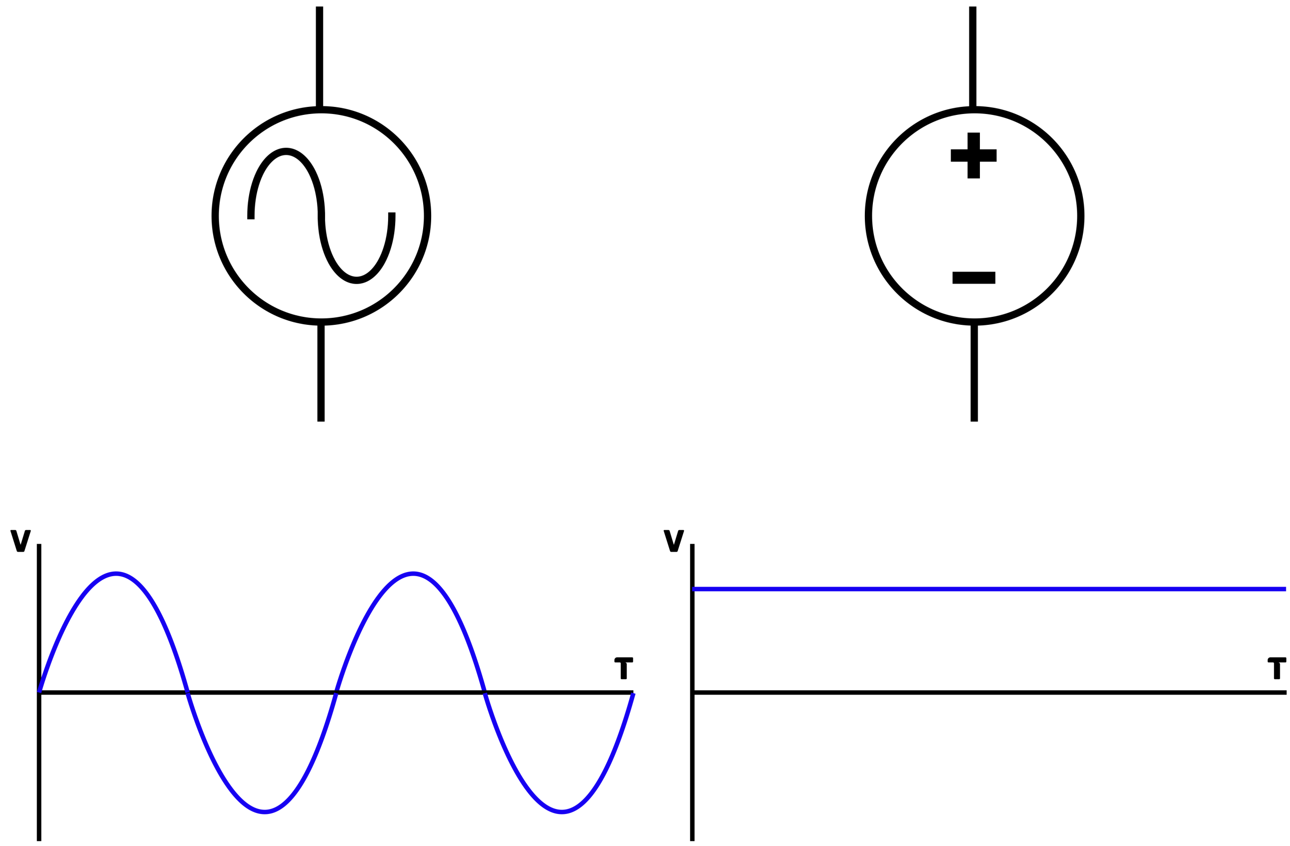
2. What is the voltage drop of each component? Also calculate the power of the circuit.



3. What is the equivalent resistance of a 20Ω, 100Ωand 42Ωcomponent, all in parallel?

0.1.2 AC vs DC

AC stands for alternating current, whereas DC stands for direct current. This is shown on a graph with the direction of flow on one axis and magnitude of voltage on the other. DC has a constant magnitude and direction of flow. This compared to a sinusoidal voltage magnitude, causing the flow of current to vary in direction for AC. AC is typically given as an RMS voltage and a frequency. The frequency is the number of periods that happen per second, typically given in Hz, where the voltage is an average value, taking the root mean square. Root mean square (RMS) represents the DC voltage that has the same power/ heating effect as the AC circuit. This is seen with power from the grid, with RMS voltages of 230V and frequency of 50Hz in the UK. Being in AC allows for converting voltages to very high amounts through long distance cables through use of transformers, to reduce thermal losses due to current.



Digital electronics is within the DC realm, but many devices still require AC. It is the standard for energy generation and for how it is sent across the grid. AC is widely used for motors, and where large voltage transformations are required, such as microwaves. Semiconductor electronics primarily work within DC.

The course will touch upon ways to convert between AC-DC and the benefits of each for different applications.

Quiz

1. What is the frequency of AC Electricity from the grid in the UK?
2. What does RMS stand for?

3. Why is AC used within the grid?

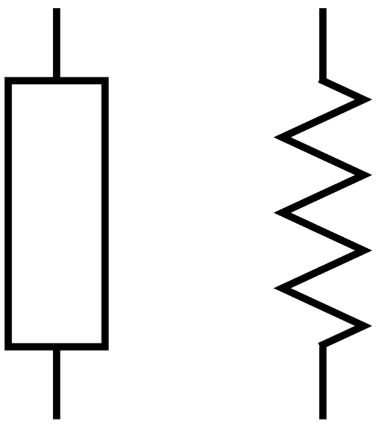
0.1.3 Resistors

What are Resistors?

Resistors are a key component to look at, which only require an understanding of equations already discussed.

Resistors are components which are rated to have a specific resistance. Therefore, depending on the circuit, there will be varying levels of losses seen from them (depending upon both the voltage and current). They can be quite important components to use when a part needs a specific voltage close to that of the source/ input, or as a way of limiting current flow.

This is an example of two main resistor representations.



This is a basic circuit, with wires, a resistor and a battery, to demonstrate V=IR. Link

In the specific example, we have a resistor of 1 Ohms and a voltage of 5V. Therefore, using $V = IR$, we can rearrange to find a current of $I = 5/1 = 5A$. Then we can find a power of $P = IV = 5 * 5 = 25W$. Each of these are seen on the simulation. Feel free to play around with it and alter values. Instructions for using the simulation program is found (here).

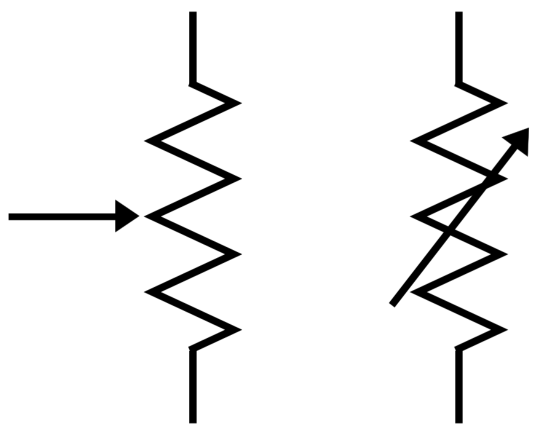
Example circuits etc

There aren't many example circuits using the above knowledge alone. One example would be if a project required a heater. Given you know the available input voltage, and the needed thermal load, you can calculate the required heating element resistance.

0.1.4 Potentiometers

A potentiometer is a variable resistor acting as a potential divider, using a mechanical dial to alter it's output resistance. There are many cases where this is helpful, such as altering speaker volume, or where you aren't certain on what voltage is needed. They typically have 3 pins, for the input, ground and output, which with the input has a resistance depending on how much the "dial" is twisted.

Digital Potentiometers, are an example of an integrated circuit (see here), which are programmed to act as a set resistance, using set steps, meaning the same resolution isn't usually attainable.



0.1.5 Capacitors

What are Capacitors?

Capacitors are another key component. They store energy as Electric Potential, with their voltage increasing towards the input voltage, as they charge. Therefore, the charge and discharge curve is nonlinear, more similar to an exponential curve.

The unit for capacitance is Farad, with typical values depending on capacitor type, but usually in the uF units or below.

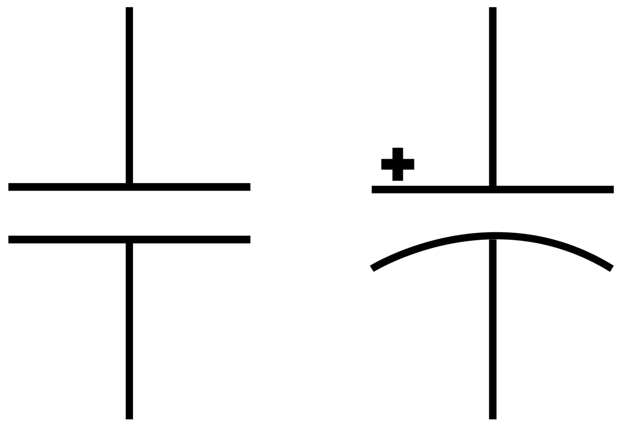
A range of physics based equations will be touched upon now.

Capacitors have a charge relating to their input voltage with the following basic equation- $q = CV$.

q is charge, C is capacitance and V is voltage. There is also the formula for energy stored within a capacitor, with the following equation- $E = 1/2 * C * V^2$, where E is energy in Joules.

A resistor is usually placed in series with a capacitor to limit the capacitor inlet current. As it charges, the ratio between its voltage and the supply voltage decreases, along with the charge current, in a curve of reverse direction to the voltage.

One of the built in simulation circuits from Falstad is helpful for showcasing the charge and discharge characteristics of a capacitor, by flicking a switch. Link



Example circuits etc

Quiz

1. How do capacitors store energy?

a) In the magnetic field

b) In the electric field

c) As thermal energy

d) They do not store energy

2. True or false, a resistor is typically used in series with a capacitor to limit current flow through the capacitor.

3. True or false, 1 Farad capacitors are commonly available.

4. Design a circuit for charging a capacitor at a maximum current of 1A, assuming a source voltage of 3V.

0.1.6 Inductors

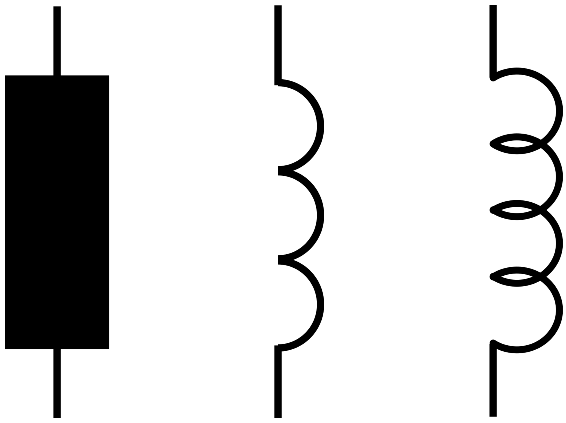
What are Inductors?

Inductors are another key passive energy storage component. These store energy within the magnetic field, and have a range of uses, often in power electronics.

The unit for inductance (L) is Henry, with typical values depending on inductor type, but usually in the uH or mH units or below.

A range of physics based equations can be used to showductance.

There is the following basic equation- $L = \frac{\Phi(i)}{i}$. There is also the energy formula for calculating the energy stored within an inductor, with the following basic equation- $E = 1/2 * L * I^2$.



Example circuits etc

0.1.7 Diodes

Diodes are widely used in electronics. The basic principle of a diode is a device/component which limits how current can flow within a circuit, such as restricting current flow to one direction. This makes them beneficial for a range of circuits, such as protection circuits, preventing unwanted reverse current flow, which could damage other components or cause unwanted side effects. They are a simpler examples of a semiconductor, where usually silicon is doped with other atoms to cause a surplus or shortage of electrons, changing the polarity of elements of the material, affecting how current flows through the diode.

There are also Light Emitting Diodes (LEDs), which work through similar principles, but emit light of a certain spectra depending upon selection. There is a voltage drop associated with this, but with considerably lower heat output, compared to filament bulbs, which heat filament up until it glows.

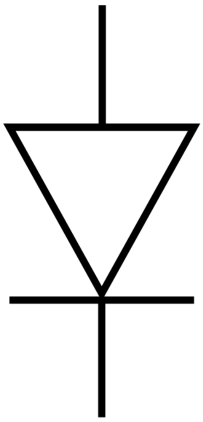
There is a common formula for calculating the resistor needed for an LED, given you know the voltage and current it runs at. This is the following-

$$R = \frac{V_s - V_f}{I_f}$$

Where V_s is the supply voltage, V_f is the forward voltage (voltage drop of the LED) and I_f is the forward current.

Different colour of LEDs have specific voltages that they work at, so resistors are commonly used, to limit the current through the LEDs, while dropping the input voltage to a level suitable for the LED. This voltage usually is between 1.8-3.3v, and is because of how the semiconductor is doped, as different dopants will causes different wavelengths of light to be emitted.

It is important to consider that diodes have an inherent voltage drop, so this needs to be considered, especially when using them with low-voltage circuits, as a typical diode can have voltage drops between around 0.4-0.7v.



0.1.8 Transformers

What are Transformers?

Transformers use the fact that a coil of wire will generate an electric field, and that a changing electric field induces a current in a coil to allow for voltage/ current conversion. Think of it as two inductors, coupled through a single core. This is typically a ferritic core to provide a magnetic path to reduce losses. These are often laminated to limit eddy currents, which are loops of current within the core, induced from the magnetic field. Lamination increases the core resistance, reducing the eddy current.

A lot of transformer design is out of the courses scope. We will assume that the transformer is ideal, although in reality, there are losses, leading to efficiencies of around 95%. This depends on how well suited a transformer is for a design.

Due to current only being induced under a changing magnetic field, Transformers only work with an AC input.

This is the basic set of equations for transformers.

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s}$$

Where p represents the input/ primary coil, and s represents the output/ secondary coil. V represents voltage, I represents current and N represents the number of turns/ coils.

There is an inverse relationship between voltage and current when there are different coil turns.

There are 1:1 transformers, where no voltage or current conversion takes place, but it isolates the input from the output, so is a safety feature often used in products. These are known as isolation transformers.

0.1.9 Analogue vs Digital

It is important to be aware of differences between analogue and digital. Analogue refers to a wave, with the fundamental characteristics of wavelength, frequency and magnitude. This value can vary considerably within a period, which is particularly useful for some applications.

On the contrary, digital is represented with either 1 or 0 (off or on). As already touched upon, the entire field of modern digital electronics is based around semiconductors, which form switches.

Signals can be sent through both methods, with a range of benefits and negatives. A lot of data can be shown in a single analogue signal, although it can be difficult to accurately read. Whereas, DC deals with two distinct boundaries, so although many more "pulses" are required to output the same amount of data, it is more reliable and easier to use/ read within logic based processing/ boolean algebra, which is touched upon later on in the course.

Sensors are often read using analogue methods, where there is an induced or dropped voltage which can vary in magnitude. This would need to be converted to a digital value for microcontroller use. A combination of digital 1/0 gives binary, which means a voltage value can be represented as a binary combination of 1s and 0s. An example of a component that can do this is an ADC.

0.1.10 Sensors

What are Sensors?

Sensors are likely to be a key component or module you use in your research, so understanding how they work and your options is important. There are a lot of sensors and sensor theory, with key aspects discussed here, with more in the further reading section.

This will be split into several sections, covering some of the major sensors, with more detail on sensors likely to be used within Chemistry related projects.

Sensors typically use resistance, capacitance or inductance to take a vast range of measurements, often using a MicroMechanical system (MEMS) to allow for this.

Temperature sensing can be done with a range of different methods, and is likely to be quite important. The most common sensors are analogue ones, where the components resistance changes along with a temperature change, although there are digital sensors for this too. There are 4 major categories of temperature sensor, which we will quickly touch upon each. There are Thermocouples, RTDs, Thermistors and specific digital ICs.

Thermistors are common, and are divided into NTC and PTC, with NTC more common. NTCs have a decreasing resistance compared to temperature, and will have a resistance rating for 25C typically along with a value for how much their resistance changes per degree. Therefore, utilising a circuit to measure this resistance allows for a relatively accurate temperature to be read.

RTDs are similar in their operation to Thermistors, but are meant for a wide range of voltages, upwards of around 600C. Many consist of a length of thin wire wrapped around a ceramic or glass core.

A thermocouple consists of two differing conductors which generate a temperature dependant voltage. They have the highest temperature range of temperature sensors, upwards of around 1800C.

Digital temperature ICs will measure a temperature and report the data through transferring it through a specific protocol, which is discussed further (here).

Humidity sensors may be used along with temperature sensors, in a single digital package, or otherwise in an analogue form, where the humidity will alter the resistance of the humidity sensor. A couple of common digital examples include the DHT11, DHT22 and AM2320.

There is a range of sensors for detecting compounds in the air, particularly important to Atmospheric research. Usually these are doped so that concentration increase of a certain gas, such as carbon dioxide, induces a voltage. Often because of the calibration involved and comparison with data, they can be quite complex integrated circuits, which will communicate via a protocol such as I2C or SPI to the microcontroller, later discussed in the protocols section. Although certain sensors may leave the conversion to the user. More modules are appearing in the market, which should help to ensure their accuracy, often key for taking useful measurements.

Photoresistors use similar method for light, where a resistance is associated with pitch black, and seperately for light. Therefore, an estimated light measurement can be attained from this. There are also photodiodes and photoresistors, each with their own benefits, like higher response rate, or lower costs.

There is a range of movement based sensors, which will quickly be touched upon. You are unlikely to need to use these too much.

One of the main cheap and widely used range/ movement sensors is an Ultrasonic sensor, which has an ultrasonic transmitter and receiver, which using knowledge of the speed of sound, measures the time it takes for sound to hit a surface and reflect, to then calculate a distance value.

There are also LiDar sensors, which are similar but known to have higher precision, which use a singular beam of light, and calculate its time of travel, these are also known as Time of Flight (ToF) sensors.

The motion based sensors discussed above are ones that are contactless, but there are also contact based sensors, which a potentiometer could be an example of, using its resistance based on a linear or rotational movement as a measurement of movement.

0.1.11 Mechanical switches

Switches are used as input devices, where depending on being open or closed, will allow power transmittion or not, by opening or closing a circuit. These can be split into many types, such as those which are usually open unless pressed, those which are usually closed unless pressed, those which switch between open and closed when pressed, and switches which you can switch to close several sets of pins/ connections.

This section will quickly talk through a few different switches/ buttons, their names and uses.

There are different switches that fit into different classifications, which will briefly be discussed.

Single Pole Single Throw (SPST) switches are ones which connect or break a connection between two single wires/ points/ terminals.

Single Pole Double Throw has a single input but two outputs which can be switched between.

There is then also Double Pole Single Throw, which is a combination of two SPSTs and Double Pole Double Throw, a combination of two SPDTs.

Now onto the different types of switch. They can mainly be split into several types being the below-

Push button- A typical button, some of which will stay closed/ pressed until pressed again, when others such as momentary push switches will only be closed as they are pressed.

Slide switches are flicked into set position, which can be two positions or multiple.

Toggle is a slight adaptation of slide switches, flicking a centred switch from one angle to another, but otherwise it works through very similar means.

Rotary switches can twist to connect a pin with a range of other pins depending where it is twisted to.

You may have a range of switches, such as a few slide switches packaged together in DIP format.

0.1.12 Digital switches/ Transistors

Switches are widely used within electronics and are what has led to the field of digital electronics. Microcontrollers may use millions of switches on a single silicon die, where discrete switches are mainly used for power electronics.

Switches are important to have control of a circuit. These are discussed in greater depth later, but they usually have an externally triggered gate, which closes a circuit. Think of a switch as a tap that allows or restricts water flow. The vast majority of these are semiconductor based, due to the low losses involved, although they are limited to DC function.

This document quickly talks over the main types in detail, so you can understand why each may be used, or why the surrounding circuit looks like it does.

There are current controlled switches and voltage controlled. BJTs are an example of a current controlled switch, where a flow between the gate pin and the emitter allows for a higher current to flow between the emitter to the collector. There is a voltage drop, which can mean losses are fairly significant at lower voltages. They are easy to use in a circuit after calculating values.

Then there are voltage controlled switches, the main example of this being MOSFETs. Current can flow after the voltage is higher than a threshold is reached in its gate. They are more complex to use, since the gate acts as a capacitor, so has to be charged, so may not function well without a properly considered gate charge circuit. Losses are related to the MOSFETs internal resistance, which can get very low, so they are typically fairly efficient.

There are other switches, mainly for high power electronics, which don't require as much depth.

Relays are an alternate form of switch, which uses an electromagnet to cause a switch to open or close. Most switches only work with DC, so these are useful for AC applications. They are another form of switch that provides electrical isolation between parts, as it is an electromagnet which pushes the switch closed.

Darlington transistors are also commonly known as a Darlington Pair, made of a couple BJT transistors, allowing higher levels of current amplification/ high current gain.

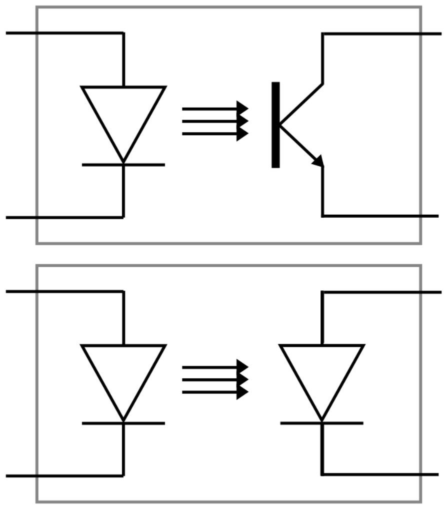
You can get arrays of transistors, such as Darlington Arrays, which is a chip with multiple Darlington transistors with common emitters. These are useful for high power or inductive loads being controlled by a microcontroller.

0.1.13 Opto-isolators

Opto-isolators, otherwise known as optocouplers, are components that use light to transfer electrical signals between two isolated circuits. This is important if the two circuits need differing voltages, or need isolating.

They work through the use of an LED and a photo-sensor/ photo-transistor, so it is light that transmits the data, to keep them electrically isolated. They are useful for measuring AC using DC electronics, so have uses within AC-DC power conversion/ supplies.

It may be worth reading the sections on photo-sensors/ photo-transistors within sensors, as well as transistors and diodes, to fully understand this.



0.1.14 Ideal vs Non-ideal/ real components

Until now, we have talked about components as if they are ideal. This means they have no losses other than expected. In reality, components have internal resistance, capacitance and inductance. For low-speed circuit design, the internal resistance is what you mainly need to be aware of. This includes the source, with certain batteries/ sources having quite a high internal resistance, which means at higher current draws, there can be a fairly significant voltage drop before it even gets to the rest of the circuit. Any of these factors can have a significant effect upon a more high-speed circuit, with capacitance and inductance altering over different frequencies.

A battery would usually have an ESR value, which stands for equivalent series resistance.

0.2 Power conversion

Power conversion could be its own course, so this lightly touches upon conversion, for a base understanding, and why it is important. Within the further reading section, there is information on Rectification, combining theory above, so is worth checking for more of a challenge, or if AC-DC conversion knowledge is necessary.

The main types of power conversion are active and linear. Active utilises both capacitors and inductors, as well as switches for efficient conversion of voltage, either to a higher or lower level, with efficiencies into the 90% possible. Whereas linear power conversion is cheaper, requires a lower number of components and is specifically for decreasing the voltage at the output. It acts as a variable resistor, to dissipate the unwanted voltage as heat, so depending on the circuit's needs, can be particularly inefficient. Therefore, if efficiency is less important than costs, or the voltage decrease is only very minimal, linear voltage converters can be an okay option. Given how easy it is to find power conversion modules (either known as step-up or step-down, whether voltage is increased or decreased), these are usually better than custom designs, as usually only a potentiometer needs altering to get necessary output voltage, with minimal losses.

For a quick active power converter insight, a switch is turned on at set ratios to charge an inductor, which then discharges to charge a capacitor, for a smoothed voltage at the intended level. The ratio between the switch on and off times will affect the output voltage.

The above mainly discussed DC to DC power conversion. To do AC to AC, a transformer is commonly used. AC to DC may use a similar method to the above but using a transformer rather than an inductor, and the use of a rectifier to convert the AC to DC.

0.3 Communication Protocols

0.3.1 Wired Communication Protocols

Communication protocols are important to interface with different devices and equipment, so a base understanding of some of the major ones would be important.

Communication protocols are a set of rules which devices follow to transfer information, allowing coherent data transfer at set speeds, depending on the use case.

It will first be useful to distinguish between serial and parallel, since these are widely referenced regarding communication protocols.

Serial means that there is a single data line/ wire used for communication in a given direction, where parallel means that there are several data lines or wires with data travelling through. Therefore, serial is typically an easier to use or implement method.

They can first be split into two main kinds, with inter system protocols being those used to have communication between devices, where intra system communication protocols are meant for between component communication.

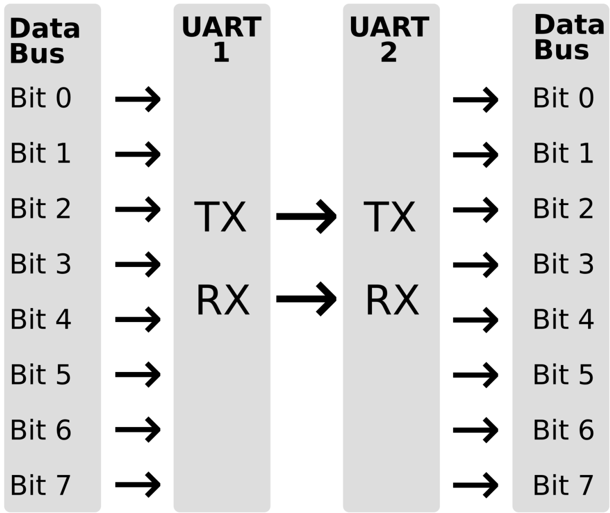
Therefore, you may use a combination of the two, depending on the project.

USB and UART are the main examples of inter system protocols, where SPI, I2C and CAN are some of the main intra system protocols. Although these are some of the main protocols, it is not a definitive list, with more niche or proprietary protocols also being around with specific benefits, or are proprietary to limit use of other companies' chips for a given application.

Master and Slave are still fairly common terms used within communication protocols, so you need to be aware of the terms, although there is a shift to alternate terms such as controller and responder, although there is not yet a set standard. Other alternatives could be on the lines of primary and secondary, leader and follower and source and sink, although the latter of which already is widely used within electronics. Because of the negative connotations of master and slave, this course uses the suggested terms of controller and responder.

USB is very widely used and is how many devices are connected to computers. It is high speed, and quite simple to implement, although requires the use of specific drivers and a powerful controller. USB 1 and 2 have 4 pins, one for power, one for ground and two for data, with data being sent serially in each direction.

UART is physical circuitry for conversion between serial and parallel data, where two UARTs may communicate with each other, communicating in serial, meaning that only two wires/ data lines are necessary for communication between two devices.



RS232 is another protocol (Recommended standard 232), which is often used within telecommunications. In general, kit is often used for connecting devices such as data acquisition or modems, the prior of which are likely to be particularly important. On creation, RS232 allowed for "handshaking", a method for checking that data is transmitting correctly, although many devices no longer require the use of this. RS232 can directly connect to the serial port of a computer.

ModBus is a protocol which was created for communication for programmable logic controllers, often for industrial use. One reasons for its wide usage is that it has no royalties and is open.

SPI is a common communication method, which can have a single controller and many responders connected to it. SPI stands for Serial Peripheral Interface, with there being 4 mains lines used, two pins for data transfer, a pin for selecting which responder the controller is communicating with and a line used as a clock. Therefore, for each device/ responder that the controller wants to communicate with, a separate select pin is required. It is a relatively fast communication protocol, but doesn't scale the best due to needing a new GPIO pin for each new device.

I2C is a similar communication protocol, which is also synchronous, like SPI, controlled with a clock from the controller. It only requires two wires for communication, the clock and the serial data line. It can communicate with many devices/ responders with just two wires, but is limited in speed and has a combined transmitting and receiving data line.

CAN stands for Controlled Area Network, and is a protocol meant for the transmission and receipt of data within a network of devices, especially for harsher environments. Due to this, it is mainly used in industrial and automotive environments, so may be used by certain equipment used. It is fast, secure and low cost, but is complex and automotive orientated.

Since not all devices have protocols that are usable together, there are chips for conversion of protocols, typically seen as modules which are often used to interface between a device and a computer. As previously mentioned, USB often requires drivers to be installed, so you should be aware that you may need to download a driver for interfacing with it.

This section will quickly go over modules/ chips you may come across for communication with these different protocols.

USB to UART modules are very common, often having a USB port on one side and 4 pins on the other. These may use a range of chips and are likely to use TTL level, which is transistor-transistor logic between the limits of 0 and VCC, which is often either 3.3V or 5V. A supplier will mention whether it works at TTL voltages, or others such as RS-232, a standard meant for telecommunications.

0.3.2 Wireless Communication Protocols

Although we won't go into too much detail, it is helpful to be aware of some wireless communication protocols and their benefits.

Wi-Fi- This is a family of wireless protocols meant for local area networking, and is one of the most widely used.

Bluetooth- Bluetooth is a short range communication protocol, meant for communication between a fixed and mobile device. It has been through several iterations, with Bluetooth 5.0 having distances upwards of 400m, but it is typically below 10m.

ZigBee- This is meant for creating local area networks of devices, with communication range between 10-100m.

LoRa- This is a long range radio protocol meant for unlicenced radio bands, with ranges in the KM range being viable, depending on the landscape and antenna used.

GPRS- This is the protocol which is the mobile standard for 2G and 3G mobile networks.

0.4 Integrated Circuits (ICs) and Microcontrollers

Along with the discrete components mentioned above, there are many integrated circuits, components with a circuit built in for specific functions. A complex example of this, which is widely used, is microcontrollers. Microcontrollers are low power processing units, with built in memory, that can be programmed to do a range of functions. These may typically be put together as a single complete unit, such as an Arduino board. An Arduino is a board with a microcontroller and passives and discrete components, to interface with basic electronics components.

Integrated circuits may do a wide range of things, such as amplification, timing, power conversion. These help to decrease the time, complexity, power consumption and often costs of a design by packaging all the discrete components necessary for its function. Usually a few passives or discrete components may be used alongside it, with references to which are found in a parts datasheet.

This section will quickly talk through some of the more important integrated circuits and their uses.

Amplifiers- A range of chips meant for the amplification of signals, usually analog signals.

Circuit Protection- A range of components meant to protect other aspects of the circuit, such as digital fuses or ESD protection.

Timing- A range of chips to provide the timing of other chips.

Data Conversion- Chips used to convert one type of communication protocol to another, or for analog-to-digital conversion.

Display/ LED Drivers- Chips meant for the driving of displays or LEDs.

Interface ICs- Chips meant for communication over different protocols, or to interface with different parts/ devices.

Communication ICs- A range of ICs and modules for wireless communication, such as Wi-Fi, Bluetooth, LoRa, ZigBee.

Logic ICs- Chips that work through low level boolean logic, for building logic based circuits.

Memory- Necessary for storing data.

Power Management- A range of chips for power management, whether this is active or linear power conversion, battery management, power monitoring or other driving chips.

Sensors- A range of chips for interfacing with analog sensing elements or combining both into a single package.

There are a range of protocols by which microcontrollers may communicate by. They also may contain a range of integrated circuits, to help interface it with different components, such as with an analogue sensor. ADCs are frequently used (often internal to a microcontroller but can be sourced as an IC).

An ADC is an analogue to digital converter, which will represent an analogue value as a bit value, depending on its resolution. This allows a voltage reading to be associated with a digital value, which can be converted to a specific unit within the program.

0.4.1 Amplifiers

Amplifiers are there to increase the amplitude of an analogue signal, often useful for use alongside analogue sensors, to take it to a voltage range readable by a microcontroller. A common component for amplification is an OpAmp, which when wired differently, can amplify a voltage difference, or amplify a signal by a specific amount. This can be negative or positive amplification.

An understanding of how amplifiers work internally is beyond the course scope, although understanding of their uses is helpful. We will touch upon the types mentioned above in some further detail. Each of the below uses an op-amp as the principle component.

The primary focus will be on the use of opamps to create amplification circuits.

Although, not an amplifier, it is important to separate two circuit elements. This is known as a voltage follower, which isolates the resistances at either end of the part, particularly important where you may try to read a resistance value from a sensor.

There are non-inverting and inverting amplifiers, which the first of which amplifies a voltage in its current direction/ magnitude, and the latter amplifies a voltage in the negative/ opposite direction or magnitude.

There are summing amplifiers which can add two voltages together.

There are also differential amplifiers which will output the difference between two voltage inputs, with a certain level of amplification.

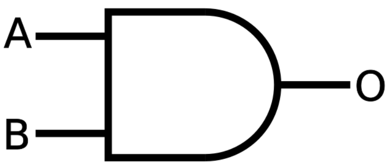
0.5 Boolean Logic

Boolean algebra is a branch of mathematical algebra, where variables are true or false, and it is centred around three main operators ”And”, ”Or” and ”Not”, and several sub-operators.

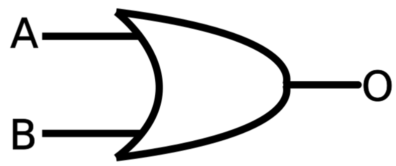
For this section, the practical elements use DDSIM, another online simulator, developed by a lecturer at the University. Although similar functionality can be done through Falstad circuit simulator, DDSIM is more streamlined and intuitive for digital/ boolean electronics. Feel free to see which you prefer for which task, as they are not completely different. https://www-users.york.ac.uk/ dajp1/Temp/ddsim.html (There is also DASIM, for analogue electronics, similar to Falstad, where it can be easier to draw up circuits, it isn't quite as easy to visualise, https://www-users.york.ac.uk/ dajp1/Temp/dasim.html).

First, we will describe what the different operations mean. Think of it as a comparison of usually two inputs, either true or false, on or off, a voltage present or not, or 1 or 0. We will use true and false, being the main terminology in boolean algebra. First, "And", is where both inputs are true, the output will be true, with any other combination having a false output. Then there is "Or", which states if either or both input is true, then the output is true. The last key type is "Not", which has a single input, where the input is the reverse of the output, true-false, false-true. Within electronics/ circuitry, gates are used to allow this logic, so you have And gates, Or gates and Not gates. There are several more complex examples, such as NAnd and NOr, which are a combination of an And followed by a Not and an Or followed by a Not. Another more complex example is an Exclusive Or (XOr), which has an output which is only true if only one input is true. A combination of transistors can make these gates, with a combination of NAnd gates creating any gate. This has become the normal, since NAnd gates are quite easy to produce from transistors.

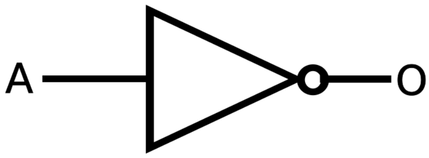
In the examples, we have used A and B as the inputs and O as output.

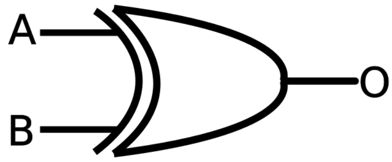


A	B	O
0	0	0
1	0	0
0	1	0
1	1	1



A	B	O
0	0	0
1	0	1
0	1	1
1	1	1





A	O
0	1
1	0

A	B	O
0	0	0
1	0	1
0	1	1
1	1	0

Boolean logic has led to modern computing, as it is a combination of logical operations done with gates. There are fairly standard circuits that people are usually challenged to make, so try to make some of these to ensure you understand boolean logic.

A famous theorem within Boolean logic is De Morgan's Theorem/ Law, which shows how AND logic can be represented through OR. We will use the below to represent this-

A & B are our inputs or "sets".

$\bar{A}$ is the compliment of A, equivalent to A through a Not gate.

$\cap$ is the intersection, otherwise known as an AND gate.

$\cup$ is union, otherwise known as an OR gate.

With the terminology explained, De Morgan's Law can be shown as the below-

$\overline{A \cup B} = \bar{A} \cap \bar{B}$

$\overline{A \cap B} = \bar{A} \cup \bar{B}$

This also helps to explain why NAND gates are typically used within circuitry to represent other gates.

If this is an area that particularly interests you, I would recommend looking at the site, Nandgame, which takes you step by step from placing gates to building a basic gate computer.

0.6 Electronics test equipment

There are a range of equipment that aids working with electronics, some may seem overwhelming at first. Understanding what they do, why and if they are needed, is important!

0.6.1 Multimeters

A very common piece of equipment is a multimeter. These are used to measure current, voltage, and resistance. When measuring current, the multimeter needs connecting in series with what is being measured. In contrast, to measure voltage or resistance, you place the probes in series with the component or circuit segment needing measuring.

There are analog and digital multimeters, with the latter being more common, and what we will focus upon.

We will talk through the main multimeter functions now.

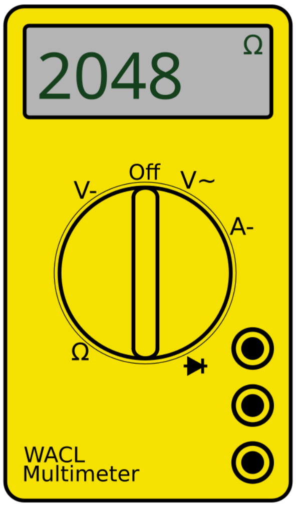
You can measure resistance, current, voltage and continuity on most, with some measuring hFE or current gain of BJT transistors. Some may also measure capacitance.

Depending on the multimeter, some will split each of the sections into specific scales, representing the max value it can show. This is so the resolution shown is close to the measurement magnitude. If, when trying to measure a value, nothing seems to be read, you may need to move this scale.

The continuity tester is used to check whether two points within a circuit are connected, or whether current can flow between them, so is helpful for checking soldering.

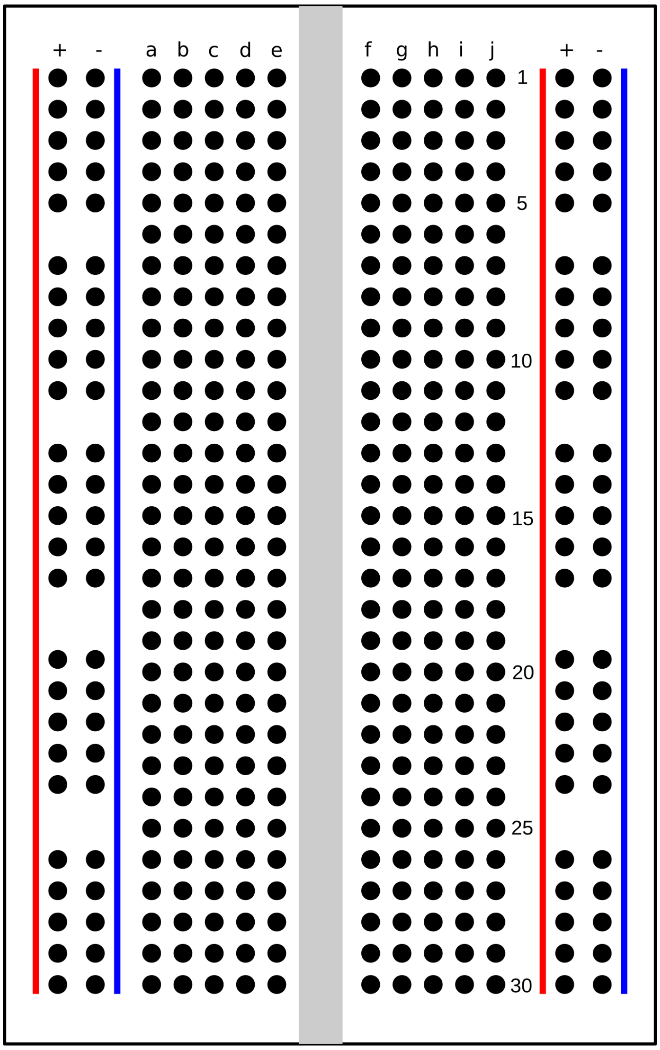
For most functions, connecting the cables to the V/Ω/mA section would be suitable as well as COM/ ground, unless it is a high current circuit, if so there is the third connection usually for currents at a maximum of 5A or sometimes 10A.

A more complex piece of equipment for complex diagnosis is an oscilloscope. These are also used for measuring voltage and current, but comparing this against time, in graphical format. The software sometimes used within this course Falstad, uses scopes which are a representation of what you would view through an oscilloscope probing a specific component or circuit element. They are particularly helpful for troubleshooting signals or inductors or capacitors.



0.6.2 Breadboards

For electronics prototyping, breadboards are seen to be pretty important, as they allow you to connect DIP components quickly for prototyping. They have many rows of 5 pins which are interconnected, so you can create an array of complex circuits with them, to test out ideas. Remember that they may not produce the most stable circuits, and would not be recommended for the field due to loose connections.



Internally, it is just rows of interlinked metal, which connect/ bridge pins together. As seen, there are two sets of 30 rows of 5 pins, with each pin on rows connecting. This means that two parts needing connecting should be on the same row. There are also power rails, which allow for 2 different voltages, and two sets of ground pins. These are convenient to access, rather than being the only suitable sections for providing power, so other rows could be used. Breadboards are specifically meant for DIP components, with the gap in the centre allowing for DIP chips to be placed, separating each of their pins. Components can be connected with male to male jumper wires. As mentioned, it is worth only attaching power when you are sure that everything is firmly connected, with no potential for shorts. There are limits to the suitability of a breadboard circuit, it is meant for lower power and lower speed circuitry.

Examples

Here are a range of example circuits to help you understand how a breadboard circuit should be wired, with increasing complexity.

The first example is an LED with a resistor, a button, and a battery.

Challenges

1. Connect a circuit with a blue 5mm led, 2 AA batteries, a 50 ohm resistor and a momentary push button.

2. Connect a circuit with 2 AA batteries, with a blue LED, resistor and button, in parallel with a red LED, resistor and button. You will need to calculate the resistor required.

Here are a range of challenges, to build up your confidence. You may need to read other sections of this course if you are struggling.

The next stage from here is a proto-board design, using vero or strip board, design of a custom circuit board, or using existing modules suitable for the design. The cost of custom printed circuit boards has decreased considerably in the past few years, through sites such as JLCPCB. This has made custom PCB design a more viable option for field use. In the further reading section, there is some detail on PCB design and resources helpful for doing this, but it is not the course focus.

0.7 Electronics safety

Safety is a key consideration when doing anything with electronics. If you are unsure, it is always best to ask rather than to assume.

As discussed, current is related to voltage and resistance through $V = IR$. The body has a resistance which can vary depending on length etc, but is relatively high. Therefore, as voltage increases, so will current if the resistance stays the same. You should always take sufficient precautions when using electronics, but especially when dealing with higher voltages, where it can be fatal. The in-person practical elements are likely to use low voltages, which are much safer. It is important to know when you don't have the knowledge or resources for a given piece of electronics and when it may be the better option to have someone else repair git. You should also consider that sometimes the best option is to replace something rather than repair it, such as when it may be dangerous, could end up costing you more if it isn't reliable, or takes a considerable amount of time to fix.

Component ratings are often not initally considered but are very important. Knowledge of ratings ensure that a selected part can take the expected power loss without damage. Therefore, it is important when selecting a resistor to calculate its estimated power drop, and select a resistor with a power rating clearly above the max predicted power losses. It is important to add a safety buffer, as circuits in reality are not ideal, so may react slightly differently than expected, such as a component having a resistance value that differs from its value. Tolerance is the percentage at which a value can differ. This is usually under 20% (it can be considerably smaller). If you are unsure, it is better though to add a safety buffer, x2 the calculated value is fairly common, as it helps to account for how the tolerances of other components affect that one.

It is important to consider that all components have losses, including wire, so this needs to be considered, with a wire or connector of suitable ratings selected. With this waste heat, also comes a voltage drop, which may also be a factor, as if high enough, can cause issues with the circuit itself.

For wires, you have different wire gauges, and sometimes different materials. Typically wires are copper, but sometimes are aluminium, with a resistance around 64% higher than copper, so looking at wire gauge alone isn't enough. Again, it is helpful to keep the chosen wire a fair bit above the power rating you require, considering that only just meeting those ratings will lead to considerable losses in the wire. And if there are cost constraints, it is important to consider that a thinner wire, which is initially cheaper, may end up costing more due to electrical losses.

There are a range of connectors too, depending on the application, each of which have their own rating. Mechanically connected, such as screw terminals, are likely to have a resistance higher than directly soldered, but can give more flexibility to make alterations.

You should be careful when handling components, as built up static can cause damage. Grounding yourself, such as touching a metal surface, can help to reduce this static potential. Anti-static wrist straps are something that can be sourced cheaply to limit the potential of causing damage.

Soldering may be something that is required for a project. Health risks are associated with all forms of soldering, so you should always solder in a well-ventilated area with the suitable equipment. If possible, although slightly harder to work with, it would be recommended to use lead free solder, reducing health risks and allowing for safer use in the field. Flux is used in solder, to help it flow, but it's evaporation produces a vapour which can be harmful if inhaled. Many soldering iron setups have extraction next to the iron, to minimise this chance of inhaling it.

Before connecting wires, particularly at higher voltage levels, running your hand along a cable to check for potential damage is important, replacing a cable if this is the case. It is also good practice to ensure both sides of equipment being connected are turned off before and during wiring, to prevent potential sparks, damage or electric shock.

Certain components can still be dangerous regardless of whether they are powered. An example of this is capacitors, which will still hold power after a circuit has been turned off, for a period of time. Therefore, ensure not to touch one/ short it. It is good practice to have bleeder/ discharge resistors connected at either end of high voltage capacitors so that when not powered, over time they will discharge. This will add some inefficiencies to a system, but improves safety.

As has already been mentioned, it is important to ensure components are not shorted, as this can cause damage quickly as the source will pump as much current as it can into the circuit, causing fast heat up. Storage of components, such as batteries in a proper case, is important to ensure that they cannot get shorted. Ensuring to check over soldered circuits to make sure nothing is bridged, such as through use of a combination of a microscope/ magnifier, and the use of a multimeters continuity checker, as mentioned previously.

0.7.1 Soldering

Being able to solder is an important skill to have. Usually, someone would first make a circuit using DIP components before attempting more challenging SMD components.

Soldering is the process of creating a metal joint between a component and a circuit board, to allow for a considerably improved electrical, mechanical and thermal connection. Solder is typically in wire form, but can also be in paste form, and it is a metal with a low melting point, allowing for a quick connection to be made with a reduced risk of damaging components.

The most basic form of soldering uses a soldering iron and solder wire. It is recommended to use a holder, to hold the parts in place, to free up hands for soldering. The soldering iron should be placed, so it heats the metal of the component and the interface metal, with solder wire placed at the other side so the solder can bridge them, making a clean connection. A clean connection should have a clean flow between the parts, rather than a ball of solder or similar.

Sometimes too much solder may be added, which can be difficulty to remove. A solder sucker can help, where you remelt the area with excess solder and then quickly press the solder sucker just above, which uses suction to pull up the excess solder. Solder wick is another option, which I prefer, as you place it between the excess solder and your soldering iron, where it ”wicks” up the additional solder. This tends to be copper, with high heat transfer, so keep hands further from the iron.

Soldering temperature is important. It is worth looking at the melting point of the solder you are using, with lead free solder typically having a slightly higher melting temperature of around 217C, depending on composition.

Although lead free solder is known to be slightly more difficult to use, being better for the environment and for your health for me definitely makes it the better option. I haven't found too much of a difficulty jump, especially if a good quality soldering iron and solder is used. Also, learning the easier option, only suited for DIY projects, which may be phased out in the future, wouldn't be as useful to learn.

0.8 Important factors/ considerations

0.8.1 Component footprints

Components can be sourced in a range of footprints, which will need consideration in design or repair. Imperial measurement is most commonly used for surface mount resistors, capacitors and inductors, with values associated with mils, which represent 1000th of an inch. In many cases surface mount components will be used with commercial products, so use of one may be required in replacement of a faulty part. Understanding their size, and your ability to solder them is important, and it is often a challenge that people follow to trial their ability. You may be able to access a soldering oven, which can help make this process easier, considering that as solder melts, it can somewhat help to pull a component into place, if it is marginally off-centred.

Components are only rated for a certain amount of heat, so care should be taken to limit thermal damage. If a component with multiple pads is being done, leaving time between soldering pins helps to prevent heat build-up.

0.8.2 Supply Chain issues

Since the Pandemic, there has been a range of supply shortages and stock issues. This has been further worsened by the fact that some companies/ institutions began to purchase components in excess to ensure they had what they needed. Being aware of this is key in electronics design, especially when a certain project may be replicated in the future.

You should consider stock at the beginning of a design project, and ordering parts early if you know they are needed, rather than waiting for design completion, as by that point it could be out of stock. The main issue is with specialised ICs and Microcontrollers, and less so with passives/ discrete components, so these can likely be ordered once you know which are required. A similar mindset should be followed for modules though, as they often have parts with low stock.

It is important to consider that the parts shortages started in 2020 are some of the worst that have been seen, mainly affecting silicon components. There was a combination of factors which kick-started the particular problems. These included increase in demand for electronics, pandemic related shipping delays, natural disasters/ fires, vast increases in the price of silicon and trade disputes between China, US and Australia. The market naturally goes through periods of higher and lower supplies, so early 2020 was meant to be a period of lower supply anyway, which further worsened things. The situation has slowly been improving.

Tips could include to use discrete or widely available parts over specific or niche ones where necessary, or modules where there are similar alternatives available.

0.8.3 Environmental considerations-

It is important to consider environmental considerations, this is in two respects. First regarding ensuring a product is suitable to the environment it is placed in, and also ensuring the design of the project has a limited carbon footprint or uses scarce, conflict materials or toxic materials.

It is important to use RoHS-certified components, luckily being most components in the market. This certification restricts the use of harmful materials such as Lead within electronics. As previously mentioned, solder is not always RoHS certified, as Lead-based solder is still commonly seen, especially in the prototype market. Lead-based solder tends to be a mix of tin and lead, whereas Lead-free substitutes the lead for some of the following- copper, silver, nickel and zinc, and others.

One way of somewhat reducing the carbon footprint could be choosing a smaller footprint, although for silicon products, this would only make a minor difference since it is likely that the silicon wafer itself is a high proportion of the carbon footprint.

There are limited steps that can be taken to reduce the carbon footprint within sourcing. Buying local will make an impact, but they have likely been sourced from long distances anyway. Therefore, it is instead worth focusing on the longevity and reusability of parts. If designing a custom circuit board, using pin headers for modules to slot into means that the modules can be reused, or replaced if there are faults, rather than the whole unit.

There is a range of aspects regarding it's placement, such as whether waterproofing is required or cooling. It is important to consider that rated temperature values are likely to be in ambient temperatures of around 25C, so an enclosed part with a poor thermal path, which is close to its rating, could fail over time. Here is where it is important to consider whether active or passive cooling may be needed, such as a small copper or aluminium heatsink, along with a fan if active cooling is required. If a fan is used, the circuit enclosure should have a hole for intake and outake of air. Some component footprints may have heatsinks specifically built for them. Thermal design/ thermal relief can be factored into PCB design too if needs be.

There are many online calculators for figuring aspects such as thermal design, which would be more time effective than learning thermo and fluid dynamics.

0.8.4 CAD and Material Design

This is a small section regarding aspects that closely link with electronics. You often require an enclosure for use of electronics in the field. Therefore, understanding different types of processes for their design would be useful.

Some of the main techniques for prototyping include 3D printing, laser cutting, and CNC milling, techniques widely used for quick prototyping of an enclosure.

3D printing mainly uses plastics, sometimes being a composite, depending on the application. One of the most common materials is PLA (Polylactic Acid), a plastic derived from plants such as Corn and Sugar Cane. It is biodegradable and compared to most other plastics, has lower contamination risk. A problem is its low glass transition temperature, which means at quite low temperatures it warps, so may not be suitable in direct sunlight for sustained periods.

Lasercutting is suitable for some types of enclosure design. Depending on laser type and power, a range of different materials, from plastics like acrylic to wood can be cut. It is a good approach when quick and less complex parts are needed.

CAD Milling is a subtractive manufacturing process where material is removed rather than added. Therefore, it is quite a wasteful process but allows a strong piece to be produced in a wide range of materials, including metals. Depending on the machine, there are limits to what geometries are possible.

There is a range of project enclosures meant for electronics projects, which can be sourced relatively cheaply, so are also worth considering to save time. These are typically seen in materials such as metals like steel or plastics like ABS. Some of these are IP rated, so can withstand different levels of water.

0.8.5 How to find a part

This is an important skill to have, especially in a changing market with parts sourcing causing many problems. You should first understand what you need, to then figure out what is available. It is useful to remember that a part with your specific requirements may not be available, so you should consider what bounds a part could work between, or whether circuit alterations are required to allow you to find parts. For parts, such as resistors, multiple can be used in series or parallel to get the equivalent value, ensuring other factors are considered.

I will quickly talk through the processes needed for part selection. This will be done in detail for a particular part, and then in less detail with other parts, as different components have different characteristics which are important. For this I will be use DigiKey, as it a major components supplier, although it may not always be the cheapest, it is known to have one of the better "search engines". Therefore, once you have found the parts you could use, you can then check other suppliers or comparison tools such as Octopart.

I will give an example part, being a resistor. Let's say I am designing a basic LED circuit, where when a button is pressed, the light turns on. It needs to use a 3.6v LIR2032 (a small rechargeable coin cell), and it needs to be a red LED. I have been told that it must have current consumption of a constant 25mA, and have a 1610 footprint. I have been told it needs to be in the colour white. I have been told it should be 1206 size (considering that this represents a size of around 0.12*0.06 inches or 3*1.4mm). Therefore, the first step you can do is open up the DigiKey homepage- Link There are many categories with subcategories within the products section, on the left-hand side. This is used when we know what category it is in, but it take some time to learn, particularly when other sites categorise things differently. Therefore, you can instead use the search bar at the top centre, type LED, and press the search button. It usually shows top results, each with a link and image, as well as listing the number of suitable parts. As we can see, there is a subsection specifically for white LEDs, so we should click on this. This opens a page with a lot of information, so it may initially be overwhelming. At the top, there are scrollable filters to see what parts are available specifically for our requirements. Below, there are checkboxes for specific but often important search criteria, with the parts are shown below this. On the top right of the criteria, I would recommend setting the filters to stacked, to see all filters at once, so you can go through each methodically. Many of these you will not need or may not understand, which is okay. You just need to scope out the specific characteristics which are important. Since some chips may have multiple LEDs on one die, firstly, it would be beneficial to find "Voltage- Forward", and select between the lowest number until 3.6V as a maximum, you can hold click to select a range, or click on the lowest boundary, and then scroll to find the highest suitable boundary and shift-click on it. Then the next suitable section looks to be maximum current, since we will likely use a resistor to limit current anyway, the maximum could be higher than 25mA, since running a component at its max rated power can decrease its longevity. Therefore, we could select between the minimum value and 40mA. We can then use "Package/Case", to look for the 1206 package size. You can then pick Apply Now. With the components shortages, it may be useful to select "In Stock", and also select RoHS compliant for environmental reasons. We can now see the available options. You should see available stock, and cost in different quantities, along with other data, such as the CCT value for the colour, depending on the shade of white needed. Although the stock number may seem a lot, for industrial customers producing many products, this might be a tiny amount, so selecting a part with plenty in stock if you feel you may need more in the future is important. I have now selected the final part. To know what resistor we may need to select, we should check the datasheet. For an LED, you can find the forward voltage vs forward current graph. We can see at 25mA, the forward voltage is around 3.25V. Therefore, we need to drop a voltage of 0.35V in a resistor. The ratio between the forward voltage and resistor voltage is 9.285714286. Given that the resistance of the LED will be $R = V/I = 3.25/0.025 = 130Ohms$. With this ratio, we need a resistor of around 14ohms. Sometimes an exact resistance value isn't available, so an alternate value may be required. You should ensure that it is as close as possible and if there isn't something close enough, you can use the parallel resistor formula/ use multiple resistors in series.

As we have talked about needing a resistor above, we can try to find one. Rather than having pre-determined specifics, we can use the data derived from the LED requirements. There will be around 25mA through the resistor, meaning power of around 0.00875W. As previously mentioned, it can be worth doubling this value to be clear of its max ratings, so we are looking for a resistor of at least 0.0175W ratings. Here, I am going to say that we don't care what size it is, but want one as cheap as possible. We want a resistance as close 14Ωas possible, in this case a tolerance of a maximum of 1% (Often 5% is used, for non precision applications). W have been told it must be a surface mount part. Luckily, in this case, Resistance, Tolerance and Power are next to each other. We want to make ensure its availability and that it is at least 0603 for hand soldering. A part is selected with plenty in stock, with all the ratings we would like, while being a cheaper part. It is important to consider that sites such as DigiKey are not always the cheapest, with this resistor costing £0.08. Although this sounds cheap, when hundreds of parts are required, this quickly adds up. Sites such as LCSC have parts such as resistors for considerably cheaper, but has worse search engine/ filters, along with typically slower delivery times. You need to factor shipping costs into the overall costs, as well as import charges.

With the above sorted, a button suitable for the task could be found. It needs to take a current of at least 25mA, and a voltage of at least 3V. In this case, we are budget-constrained to under £0.20, so a tactile switch would be the best option. As can be seen, a switch has been found, rated for 50mA, so again, following the double the expected value for the rated value, to account for plenty of unexpected deviance.

We have now selected several parts, using just the criteria required. As has been seen, there is a vast array of other filters that can be selected. As already mentioned, DigiKey has plenty of components on offer, and a good search function, but is certainly not the cheapest option. It can always be used to get a better idea of what you are searching for, to then search elsewhere, such as Octopart using a specific part number.

This section will now quickly talk through some of the key factors/ variables you should look for in a range of parts-

You should consider that power and current ratings sometimes regards the peak power seen but sometimes the average. Voltage ratings usually are relate to the peak voltages.

Resistors- Resistors are a basic component, but still have many filters, with the key ones touched upon now. As touched upon, the manufacturer can be pretty important, using one such as mentioned above. Then resistance is obviously key. Tolerance is the max percentage deviance with the resistance, so lower is better. Power is its max power rating usually at ambient temperatures. The temperature coefficient is how much its resistance can change due to a temperature change. Package or footprint is regarding its size and the specific footprint as mentioned in the datasheet.

Capacitors- Capacitors have a few similar characteristics such as tolerance etc. Unique factors include ESR similar to impedance, which is the internal resistance at a given frequency, voltage rating which is the max voltage it can be charged to, ripple current is the current it can withstand at a given frequency and polarity, as some capacitors are restricted to the direction of current flow.

Inductors- Again, these have quite a few of the same criteria as already mentioned, one of the main things is current rating which is the maximum current the inductor wire can take (constantly/ on average) and saturation current is where the magnetic field is no longer proportional to current.

0.8.6 Finding Arduino Libraries

Arduino IDE is a widely used microcontroller development platforms, particularly for DIY projects. This makes it considerably easier to find libraries for a specific chip or module.

Often, going onto the page for a module you would like to use for a chip should give details on its usage, as well as how to install libraries.

Within the Arduino IDE, there is a search function for libraries too, which should have many of the more common ICs/ modules.

0.8.7 Circuit Design Process

Now that many components have been discussed, this section will talk about some techniques, tips, and processes involved in circuit design.

It is important to first consider what are your requirements. What function does a given circuit need to have, what environment does it need to be suitable for, what budget does it need to adhere to, what interaction does a user need to have with it, how easy will it be to make, can parts actually be sourced for it, and what restrictions are there regarding input power, how much processing power is required, how easy should it be to program, are there any niche libraries needed for it. Each of these factors will be split up and talked about individually in some detail. Remember that it is very hard to get a "perfect" circuit. There are many variables and factors at play. It can be a bit of a balancing act or figuring out what factors are key to the project.

As a first tip, I would recommend writing answers to the above questions, and then for each writing what you would like the circuit to have regarding that factor, and what is the "minimal viable product".

First, figuring out what function the circuit needs to have is going to decide what type of components are needed. With this, it is worth seeing if there are already circuits out there which do what you would like or are close to. An example could be checking for open-source designs which could be adapted to your specific use case.

Regarding what environment it needs to be suitable for, there are multiple unique factors. These include areas such as does the enclosure need to be waterproof? Does there need to be a heatsink or fan due to high expected temperatures? Does it need to use all SMD components to be as low profile as possible? Does a more specialist circuit board need to be produced to adhere to certain standards? What fail-safes need to be integrated into the design?

Considering the budget, it is worth not making a design that goes right to that, as there needs to be extra in case there are any issues with a first design. You need to factor in that multiple parts may need purchasing if there is a minimum order quantity. You should also consider whether the budget would be restrictive for what needs to be done. It is important to figure out whether saving money or saving time is more important, such as whether using modules or custom designs would be better.

You need to figure out what interface it needs for someone to use it. This could include considering whether it needs to transmit data through a wired or wireless protocol? Does it store data on an SD card or inbuilt storage that needs connecting to a computer? Does it have a small display and buttons for setting things up, or is a computer/ external device required for its function?

Depending how easy would it be to make, you need to consider whether an external service should solder the board, whether it can be done by hand or whether a heat station should be used. This may make you focus on a specific design, such as using DIP components or focusing on SMD components.

A more important question than usual is, can components actually be sourced? There are tips elsewhere in this course on the matter, but it is worth remembering that this should be quite a key parameter, as sometimes more novel approaches may need to be taken, as the typical route may not be viable with parts shortages. Having a quick feel on stock levels for the kind of parts you need could be a worthwhile exercise before you get too far into a design.

It is important to be aware of how power needs may restrict the design, whether it is for mobile uses, so there is a restriction on how powerful components can be/ ensuring that high-efficiency parts are selected, or whether there is only a specific voltage input, so deciding what power conversion circuitry is required or viable.

Selecting what microcontroller to use is important. Certain platforms, such as those compatible with the Arduino IDE can help to speed up design, with the wider availability of libraries and easier-to-use code. Within different platforms, there can be microcontrollers of varying performance, so understanding your needs regarding this is important. This could be related to whether an 8bit, 16bit or 32bit microcontroller is required, the latter of which should work for most endcases.

0.9 Further reading

This section provides further reading into advanced topics. Although you may not need to make a circuit using the below, understanding of them may be beneficial. The below circuits may help you to solidify your understanding of the key components mentioned above.

0.9.1 Rectification

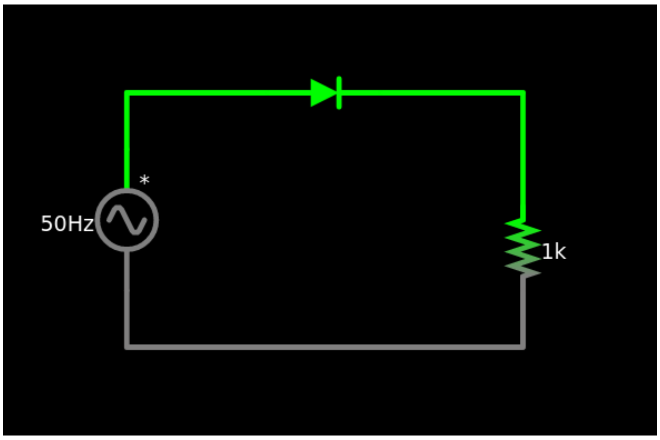
What is Rectification?

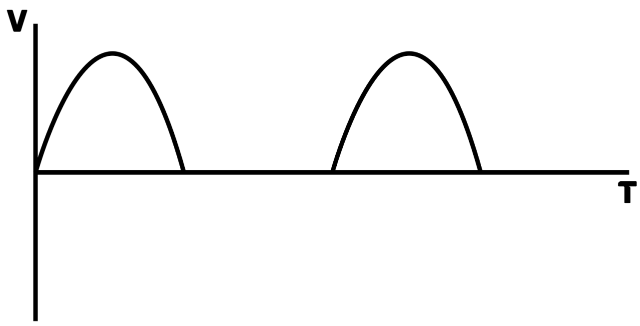
Rectification is the process of converting AC to DC, commonly used in power supplies, such as a phone or laptop charger. This is very important due to digital electronics requiring DC to function. Although diagnosis of AC circuits should not be done without the necessary training, understanding of how AC circuits function is important for safety and to better understand the use of components.

This circuit uses components which have already been discussed earlier in this document, so for further explanation, refer back to the appropriate sections.

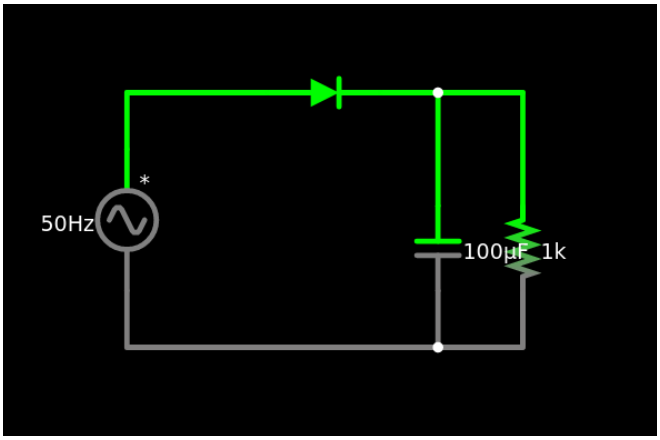
For this AC-DC conversion, the alternating current needs to be converted to flow in just one direction. Therefore, a key component in this process is a diode (This will provide a hyperlink to the diode section).

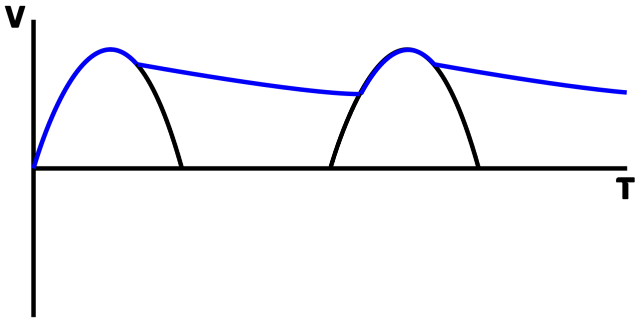
The most basic form of rectifier is a half-bridge (otherwise known as half-wave). This uses a single diode in series with the load, to limit current flow to one direction. Therefore, the output wave will be the positive side of the sinusoidal wave, with the average voltage at the output around half of the RMS voltage, although in a form unsuitable for most DC circuits.



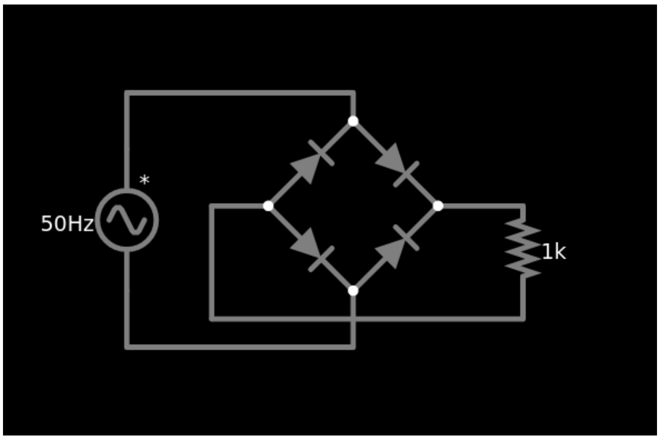


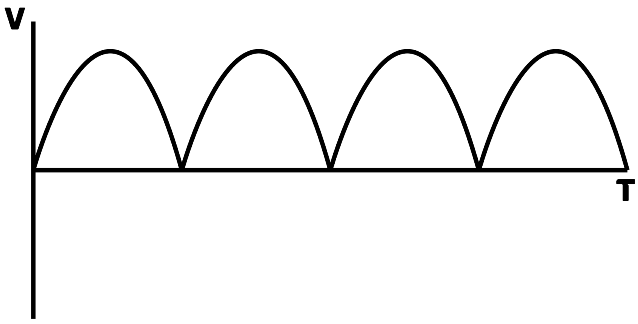
A half-bridge circuit can be improved through use of filtering, with the addition of a capacitor to smooth the output voltage. This capacitor is added in parallel, where it is charged by the voltage, which it will then output this when the output drops below its own voltage. This means that the output voltage can get closer to being a smooth DC voltage. As previously mentioned, even if perfectly smoothed, the max voltage that could be attained is half the RMS voltage.

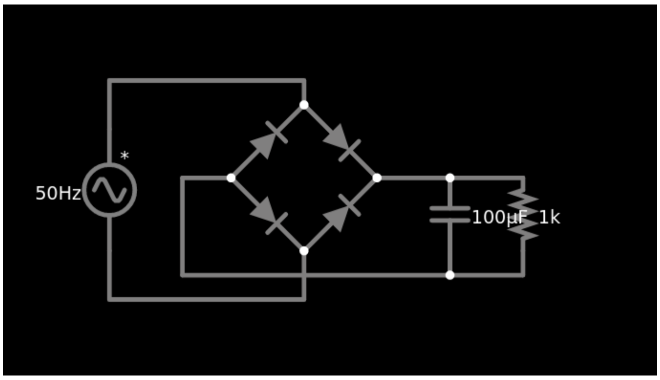


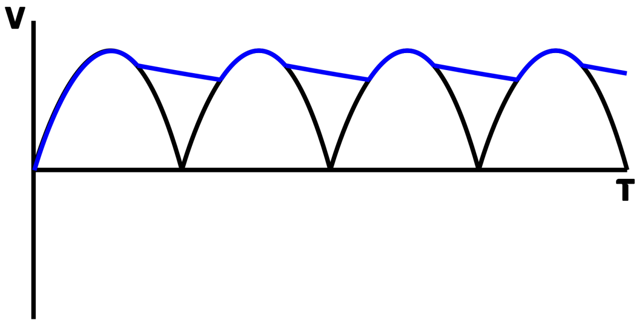


A full-bridge rectification circuit is yet again a further improvement. These utilise four diodes, meaning that whichever way the current flows at the input, it will be fixed at the output. Therefore, there will be a sinusoidal voltage magnitude, but only in the positive axis. This can again be smoothed with a capacitor, and if efficiently smoothed, will have an output close to RMS.









Example circuits, applications and considerations

This section will quickly look at applications of the above mentioned circuits.

Rectification circuits are used a considerable amount, especially for AC-DC power supplies, as an initial stage to convert AC to DC. Due to this, their main use is within mains connected power supplies. Another example is a dynamo torch, where the AC power generated from the motor needs rectification to suitably power an LED.

It is likely that in most cases a full-bridge rectifier would be used rather than a half-bridge rectifier, unless initial costs were a major consideration.

Because of variance in the manufacturing process, even within a single product, it is commonly considered best practice to use a full-bridge diode package, where there are four equal diodes within one part.

Rectifiers are generally used as part of a more complex power system, usually as an earlier stage.

Simulations

Below are several simulations to have an experiment with to help your understanding of Rectification.

Half-Bridge rectifier at 230V RMS, 50Hz- Link

Half-Bridge rectifier at 230V RMS, 50hz with capacitive smoothing- Link

Full-bridge rectifier at 230V RMS, 50Hz without smoothing- Link

Full-bridge rectifier at 230V RMS, 50Hz with capacitive smoothing- Link

Quiz

1. What is the main benefit of a full-bridge rectifier over a half-bridge rectifier.

a) It is cheaper to build.

b) It allows for full utilisation of the input voltage.

c) It uses fewer components.

2. Why are smoothing capacitors useful? (There may be more than one right answer)

a) They allow for a more constant output voltage.

b) They increase average power output.

c) They reduce output ripple.

3. True or False, it is known to be better to use several diodes individually rather than packaged together as a full bridge rectifier package.

4. True or False, rectifiers can be used to also convert DC to AC.

Challenge- Using Falstad or hand drawn, design a full-bridge rectifier with voltage variance/ ripple lower than 10%, working with an AC voltage of a peak value of 326V, at 50Hz.

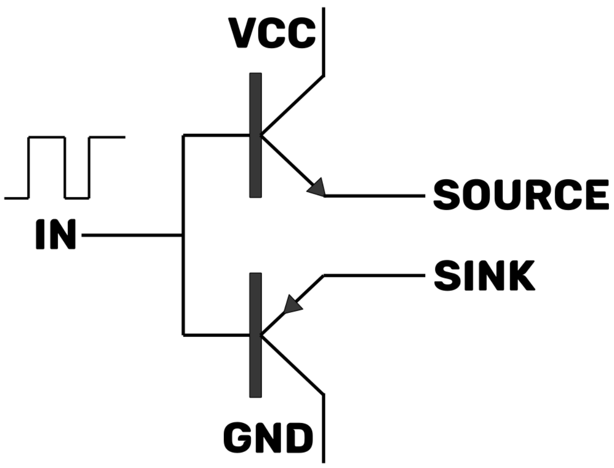
0.9.2 Gate Driving

What is Gate Driving?

Gate driving is necessary for using MOSFETs in high-speed circuits. As mentioned earlier, MOSFET gates have an inherent capacitance which requires charging in order for the gate to "switch". Therefore, for fast switching, it may require large amounts of current, which a microcontroller may not be able to supply. Therefore, there are integrated circuits with common methods to allow for these to be charged safely. One of the main simpler methods is called a totem pole gate driver. This uses two BJT transistors, one used to charge and the other to discharge the gate. BJTs are used because of their simplicity and ability to amplify the input current using an external source. Even then, it is important to use a resistor to limit the gates charge current.

This section has been written as it references a range of components and knowledge from the main sections of the course, so is a useful way to better understand theory.

Here is a circuit of it in action, feel free to play around with it- Link



The method shown above isn't the only viable option, but is one which is widely used and one of the simpler ones to understand.

0.9.3 555 timer

555 timers are adaptable ICs, for a range of timing techniques, that may not require a whole microcontroller. Although understanding the internal structure of a 555 timer is out of the scope of this course, understanding how and why they are used could be beneficial. Depending on how it is connected to, it

can be used for outputting waveforms of different frequencies, or as a timer.

0.9.4 PCB Design Basics

Although this course won't go into too much detail on PCB design, again it is useful to be aware of.

The cost of custom PCB production has reduced considerably due to the increase in prototype PCB services. JLCPCB was one of the first to make this change. The reason their model is viable is that they use excess board space, left from larger customers, so most costs are due to the set-up, rather than the material costs. It also means that it is reducing waste.

A couple of free PCB design tools include EasyEDA and KiCAD. If you prefer open-source software, KiCAD is a good option, although otherwise, EasyEDA is pretty easy to get started on, is free for even its advanced features, and has links to both LCSC and JLCPCB to get you going quicker. A considerable amount of time can be spent finding suitable package footprints or designing footprints. This is where EasyEDA simplifies things, with most of the parts in LCSC's library being available as a part you can search for and drop into the design. Even if it is an external part, there are many community part footprints and schematic designs. For community derived parts, it is always worth reading the datasheet to ensure it matches up with that design. Most datasheets should provide information on the design of a suitable footprint for a PCB.

0.10 Resources

There are many resources within electronics which can be helpful, both for learning more, but also for a range of different aspects. This will list some of the ones particularly worth looking into, and what they are for.

0.10.1 Manufacturers

It is useful to be aware of some of the main reputable manufacturers of components and modules. This is not a definitive list, but in most cases you should be able to trust components from these manufacturers. This focuses on mainly larger manufacturers, so there are many more trusted manufacturers. Keep in mind that there are fake components in the market, so ensure you source them from a trusted supplier, talked about in the section below! As touched upon in the finding components section, most parts through a site such as DigiKey should be reliable.

Resistors- Yageo, BOURNS, Panasonic, ROHM, Samsung, TE Connectivity, Vishay, Walsin.

Capacitors- Rubycon, Panasonic, Hitachi, Sanyo, Vishay, Nichicon, NCC, Wurth, Illinois Capacitor, Cornell Dubilier.

Inductors- Wurth, Walsin, Vishay, TDK, TE Connectivity, Pulse Elec, Murata Electronics, BOURNS, EATON.

Transistors- Vishay, TOSHIBA, Texas Instruments, STMicroelectronics, ROHM, RENESAS, onsemi, NXP Semicon, Nexperia, Infineon, Diodes Incorporated.

Diodes- Vishay, TOSHIBA, STMicroelectronics, ROHM, onsemi, Nexperia, Microchip Tech, Infineon, Diodes Incorporated.

Sensors- Infineon, Analog Devices, OMRON, Texas Instruments, TE Connectivity, NXP, Microchip Technology, Murata, BOSCH, STMicroelectronics.

Microcontrollers- Microchip, ATMEL/AVR, NXP, STMicroelectronics, Espressif Systems, Infineon, Altera, Raspberry Pi, RENESAS.

ICs- Texas Instruments

0.10.2 Suppliers

Starting with several trusted parts suppliers.

Arrow Electronics- Europe based Electronics components shop.

RS Components- UK Based Electrical and Industrial components shop.

Mouser- US based Electronics components shop.

Farnell/CPC- Electronics components shop based in several regions.

LCSC- Electronics components shop based in China, with links to JLCPCB and EasyEDA, offering lower costs than most other suppliers for larger orders.

Digi-Key

Rapid- UK Based Electrical and Industrial components shop.

EuroCircuits- Lower cost PCB manufacturer based in Europe.

JLCPCB- Low cost PCB manufacturer based in China

Aisler- Lower cost PCB manufacturer based in Europe.

Most of the above focus on singular components, which may not be what you are looking for. If you are looking more for modules or DIY components, there are a range of other trusted retailers.

HobbyTronics- UK Based hobbyist electronics shop.

Bitsbox- UK Based hobbyist electronics shop.

Adafruit- US Based company producing a range of boards/ modules.

Sparkfun- US Based company producing a range of boards/ modules.

Pimoroni- UK Based module maker and hobbyist electronics shop.

There are a couple of sites used to find stock of components across suppliers, while comparing their costs. Within these tools, there can be a range of other suppliers mentioned, quite a few of which being resellers, where you may pay more, but they often have parts in tight supply.

These could be thought of Electronic Part Search Engines.

Octopart

Findchips

OEMSecrets

EasyBom

0.10.3 Electronics Software

There are several bits of Electronics Software mentioned below, whether it is for simulation or PCB design.

Falstad- Free online electronics simulation program, which is easy to visualise what is happening in a circuit.

LTSpice- Free and powerful electronics simulator, although slightly dated presentation, produced by LT.

TinkerCAD- Simple online software for basic 3D design and electronics design/ simulation.

MicroCap 12- Although it can be seen as abandonware, it is now free, relatively recent and a powerful piece of software.

KiCAD- Free and Open Source PCB Design Package

EasyEDA- Free and easy-to-use PCB Design Package with links to both LCSC and JLCPCB.

subsectionFurther learning sites

Another helpful resource could be additional places to go to learn further.

Allaboutelectronics

Hackaday

Hackster.io

There are a range of helpful YouTube channels, such as the below-

GreatScott- Page with many tutorials and projects, in quite a lot of detail, although it can be quite complex for beginners. But if you like being taught through a project-based idea, this is worth checking out.

Electronoobs- Another project based channel, teaching you a range of things.

EEVBlog- One of the biggest Electronics Video Blogs, covering a range of areas at different levels, from an Electronics Engineer. Known to be unscripted, and ”off-the-cuff”, but pretty informative.

Adafruit Industries- Channel set up by Adafruit, discussing electronics and their modules.

0.11 Necessary software

Throughout this document, you are encouraged to check simulations through Falstad. Falstad is a web-based, simple to use but powerful circuit simulation program. It was designed by Paul Falstad and is free to use.

It has been selected because of its ease of use and ability to represent information about the circuit in a clear and helpful way.

This can be found through the following link- Link

It provides a visual and easy way to represent circuits, with the ability to plot voltage vs current for set positions or components. There is a vast array of sample circuits which can be looked at for reference too. The simulations mentioned in this course use this software, so a brief understanding of how it works would be useful. Each component will have nodes/ squares where other components should be connected to. These components can be found in the draw section, and you can click and drag to alter its size.

LabVIEW is required for the practical part of this course. LabVIEW is a graphical programming platform, intended for Test and Measurement, so was selected as a suitable program for testing out the skills developed through the course. This will need to be installed, using the Universities licence, which the steps can be found through the following resource- Link

LabVIEW will be used to interface with an Arduino, rather than using a programming environment such as the Arduino IDE. It is useful to mention that platforms such as this are often used to program microcontrollers, with Arduino IDE based on C++.