



POWER AND ENERGY ELECTRONICS

CP3666

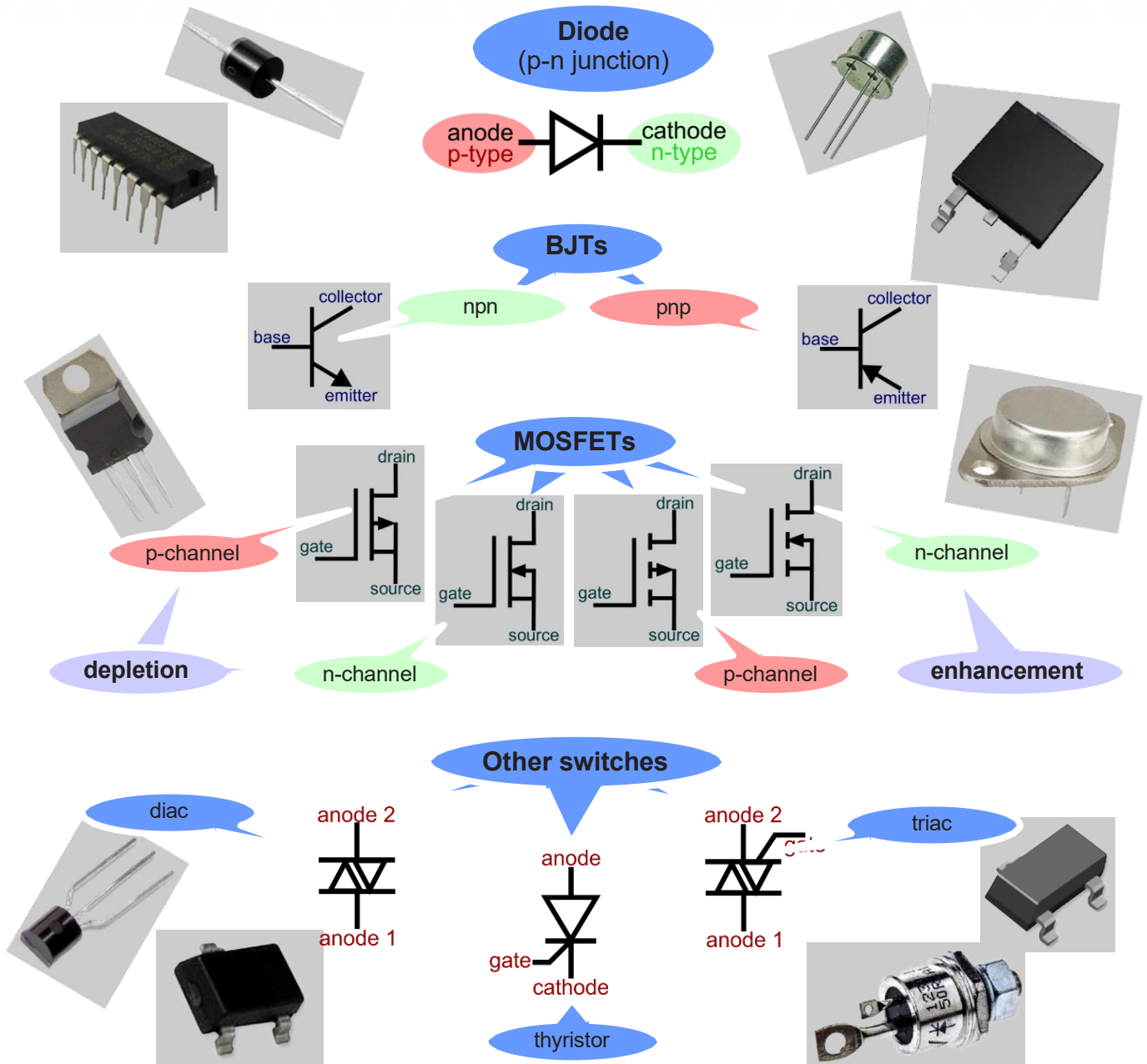
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Introducing the Components



The hardware:

- Semiconductors used in the electronics industry come in two types, n-type or p-type, depending on which impurities are diffused into the crystal, usually silicon.
- A p-n junction is a single semiconductor crystal where one end is p-type and the other n-type. Its distinctive properties are exploited in the components shown above.
- Semiconductors have a significant weakness - temperature rise. If they get too hot, they can be irreparably damaged. They are often mounted on 'heat-sinks', large metal plates which help them to lose heat and stay cool.

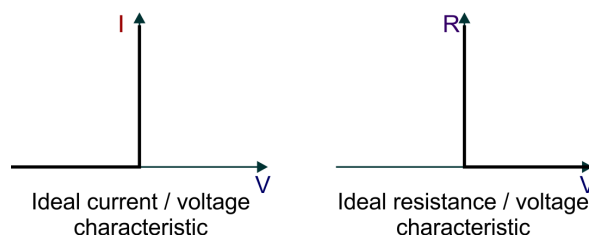
Introducing the Components

Diodes:

As the name suggests, these have only two terminals, the anode and cathode.

They are 'one-way valves', allowing current to flow only one way through them, from anode to cathode. More precisely, they offer a huge resistance to current flow in one direction (cathode to anode,) and a very small resistance to current flow in the other, from anode to cathode.

The following graphs show the ideal characteristics of a diode:



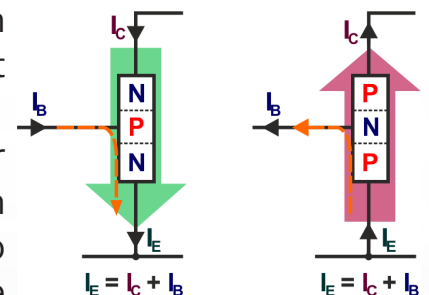
There are a number of different types of diode:

- Small signal diodes - Lower power rating, up to 500mW;
 - Superior performance at high frequencies;
- Power diodes - Handle much higher currents and power, up to several kilowatts;
- LED - Light-emitting diodes convert electrical energy into light at very high efficiency;

Bipolar junction transistors (BJT):

Come in two types, npn or pnp, depending on the way in which the impurities are added.

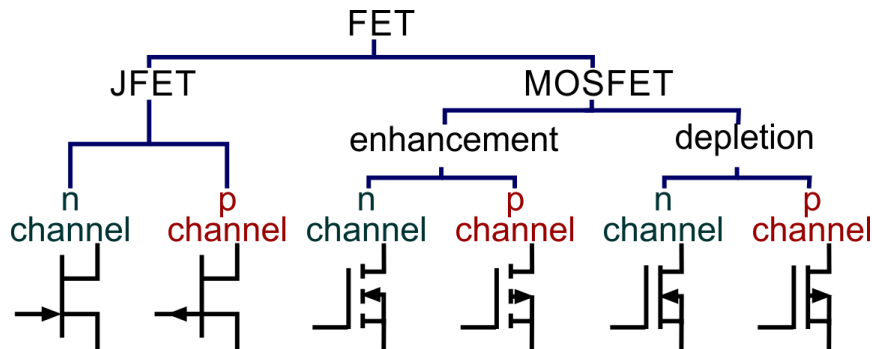
- Each has two p-n junctions, (n-p /p-n) for the npn and (p-n/ n-p) for the pnp, made by diffusing impurities through a photographically-reduced mask into the silicon.
- Each has three regions, called collector, base and emitter.
- Various 'leaded' and 'surface-mount' packages, such as TO92 and SOT-23, are used to house the silicon crystal. The manufacturer's data sheet identifies the terminals.
- The diagrams show the direction of current flow in npn and pnp transistors. The pnp transistor can be thought of as a mirror-image of the npn device.
- The transistor is a current amplifier. The collector current, I_c , is typically around fifty times bigger than the base current, I_b . The emitter current, I_e , is equal to the sum of base and collector currents. Since the base current is much smaller than the collector current, the emitter current and collector currents are roughly equal.



Introducing the Components

Field-effect transistors (FETs):

have a bigger family than BJTs as the following diagram illustrates:



- All share the same principle - the resistance of the conducting channel between drain and source depends on the voltage applied to the gate. As a result, this gate voltage controls the drain current.
- The family has two branches - JFETs and MOSFETs. In both, the gate terminal is insulated from the conducting channel. The mechanism creating the insulating layer is different:
 - In JFETs (Junction FETs) - it is a reverse-biased p-n junction;
 - In MOSFETs (Metal-Oxide-Silicon FETs), it is a thin layer of insulating material.
- In general, n-channel FETs switch faster than p-channel devices because electrons move faster through the silicon lattice than do holes.

MOSFETs:

- Are further subdivided into depletion mode and enhancement mode types:
- Depletion mode devices are similar to JFETs - the drain current is at its maximum when the gate voltage, V_{GS} , is zero. As V_{GS} increases, drain current decreases.
- Enhancement mode MOSFETs have the opposite behaviour - no current flows when V_{GS} is zero but it increases as V_{GS} increases.
- Switch faster than BJTs because the drain current is a flow of majority carriers, (electrons in a n-channel device, holes in a p-channel device,) not minority carriers. (Minority carriers can experience delays in passing through the silicon lattice.)
- Have an extra terminal, the 'body', usually connected internally to the source.

All FET devices are viable but production issues mean that p-channel depletion MOSFETs are rare. The most common format is the n-channel enhancement MOSFET.

Introducing the Components

BJT vs FET:

- **FET:**
- The gate is insulated from the remainder of the device, as described earlier;
- So the input current is minute.

It is a **voltage**-controlled device - the drain current is controlled by the gate **voltage**.

- **BJT:**
- Is a current amplifier - a small base current controls a much larger collector current;
- The input current flows through a forward-biased p-n junction, a small resistance, and so the resulting input current is relatively large;
- Hence, the BJT has comparatively high input power requirements.

It is a **current**-controlled device - the collector current is controlled by the base **current**.

Thyristors:

The thyristor can be viewed as a combination of two BJTs connected so that it 'self-latches'. When one transistor switches on, it switches on the second, which in turn then keeps the first one switched on.

It is sometimes called a SCR (silicon-controlled rectifier). That is a good description of what it does - acts as a rectifier when it receives a control signal. However, the name SCR is a brand name given to one particular kind of thyristor and so it is best to avoid the name. It has three terminals called 'anode', 'cathode' (as in a diode) and 'gate' (the control input).

Triacs:

The thyristor shares a property with the diode - it conducts only in one direction, from anode to cathode. In DC circuits, this is not necessarily a problem but in an AC circuit it means that conduction, and so power delivery, can take place for a maximum of 50% of the time.

A triac behaves like two thyristors connected in inverse parallel (back-to-back), sharing a common gate terminal. It has three terminals, called 'anode 1' (or 'Main Terminal 1', cut to 'MT1'), 'anode 2' (or MT2) and 'gate'. Conduction can take place in both half-cycles of the AC supply, improving the delivery of electrical power.

Diacs:

The diac behaves like two back-to-back diodes, modified to conduct only above a particular voltage, typically around 30V. Used to trigger thyristors and triacs, it provides sharper trigger pulses and hence more rapid switching.

An important issue! These components are mass-produced. As a result, their properties vary. The circuits shown in this course function for the vast majority of components. Occasionally, be prepared to vary the odd resistor or capacitor value to optimise the performance of the circuit. Consult your instructor first!



WORKSHEETS



WORKSHEETS

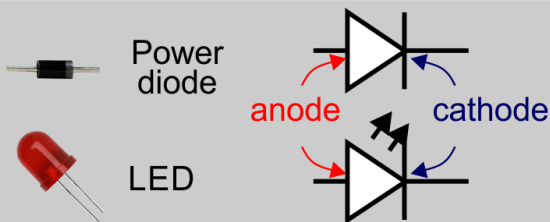
Worksheet 1 - The p-n Junction Diode



One way

The module begins by looking at the behaviour of a p-n junction, the structure at the heart of the semiconductor components studied elsewhere in this module.

Two very common devices, the power diode and the LED (light-emitting diode) owe their behaviour to p-n- junctions.



The cathode is marked by a stripe on the body.

The cathode is the shorter lead.

This worksheet reveals the remarkable behaviour of the p-n junction, behind the operation of the power diode and for the LED.

Over to you:

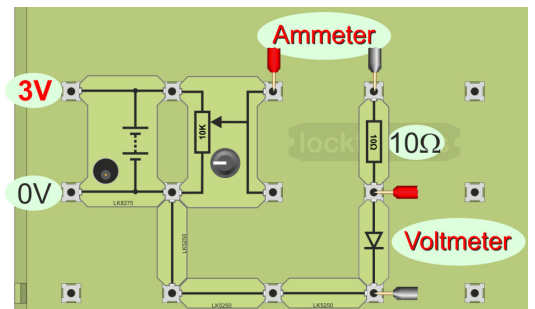
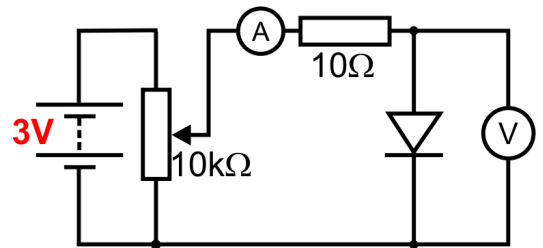
- Build the circuit shown opposite.

The variable resistor allows us to change the voltage applied to the diode.

Set up like this, with the anode connected to the positive end of the power supply, the diode is **forward-biased**.

The 10Ω resistor protects the diode from damage by excess current.

- **Set the power supply to 3V!**
- **Before you switch on, select :**
 - The **20mA DC** range on the ammeter;
 - The **20V DC** range on the voltmeter.
- Turn the knob on the variable resistor fully anticlockwise, to set the supply voltage to zero.
- Turn the knob slowly clockwise until the current through the diode reaches 2.0mA. Then read the voltage across the diode.
- Turn the current up to 4.0mA, and take the voltage reading again. The current will change rapidly for a tiny change in voltage! **Be careful - turn the knob on the variable resistor very gently!**
- Continue in this way, increasing the current in 2mA steps, up to 20mA, taking the voltage reading each time.
- Write your results in the table given in the Student Handbook.

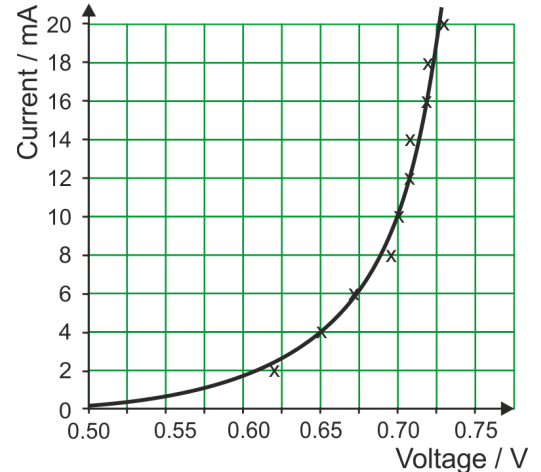


WORKSHEETS

Worksheet 1 - The p-n Junction Diode

So What?

- Plot a graph to show your results.
- Draw a smooth curve, like the one shown, using your plotted points as a guide.



- Now, turn the voltage down to zero, and switch off the power supply.
- Remove the diode and replace it the other way round, so that it is **reverse-biased**.
- Switch on the power supply and turn the knob on the variable resistor slowly, to increase the supply voltage to its maximum value.
- Notice the current reading on the ammeter as you do so! (No need to plot this on a graph!) Comment on your findings in the Student Handbook. Compare the performance of this diode with the ideal characteristics shown in the Introduction.

The power diode is a 'one-way valve', allowing current to flow through it in only one direction. When forward-biased, a power diode conducts, with a voltage drop of about 0.7V across it. When reverse-biased, it does not conduct at all (for low voltages.)

(For a resistor, it does not matter which way round it is connected. It does exactly the same thing whichever. Try it !)

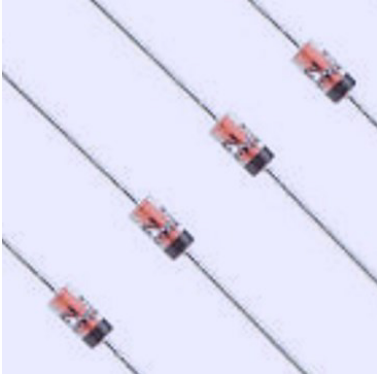
Next you are going to carry out the same investigation but using a light-emitting diode (LED.) Look underneath the 5V LED component . It has a 470Ω resistor connected in series with it, to protect it from high currents.

Challenge:

- Using the same circuit as before, plug in the LED so that it is forward biased.
- Repeat the investigation, but this time increase the current in 0.2mA steps, to a maximum of 2.0mA.
- Measure the voltage across the LED itself (not the LED and 470 ohm resistor) at each step and record your results in the table provided in the Student Handbook.
- Plot them on a graph and draw a smooth curve, with the same shape as before, using the points as a guide.
- Finally, connect the LED the other way round, so that it is reverse-biased, and comment on its behaviour.

WORKSHEETS

Worksheet 2 - The Zener Diode



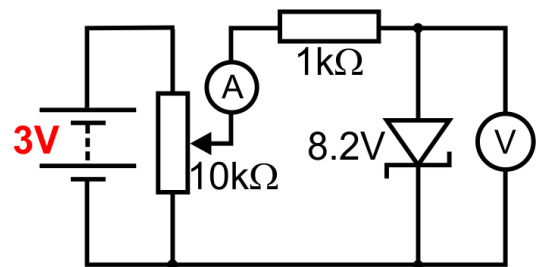
The zener diode is remarkably unremarkable. It does exactly what all other semiconducting diodes do. It passes a current when forward biased and blocks it when reverse-biased, unless the reverse voltage is so great that the diode breaks down.

However, for 'normal' diodes, reverse breakdown usually occurs at a high voltage, e.g. 400V, and can damage the diode. The zener diode is designed to break down in a controlled manner at a precise and much lower reverse voltage.

Over to you:

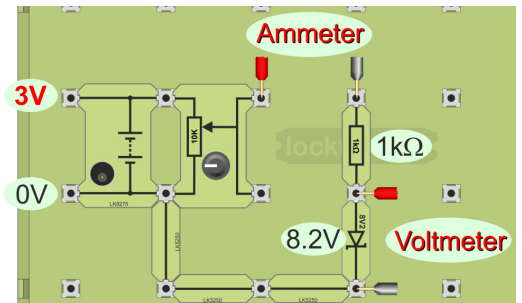
- Build the circuit shown opposite.

Set up in this way, the zener diode is **forward-biased**. The variable resistor allows us to change the voltage applied to the zener diode, while monitoring the current flowing through it and voltage across it.



Make sure that the power supply is set to 3V!

- **Before you switch on**, select :
 - The **20mA DC** range on the ammeter;
 - The **20V DC** range on the voltmeter.
- Turn the variable resistor knob fully anticlockwise to set the supply voltage to zero.
- Switch on the power supply and turn the knob **slowly** clockwise to increase the voltage.
- Watch the ammeter reading as you do so.
- Stop increasing the voltage when you observe a current flowing through the diode.
- Write down the voltage reading at which this happens in the Student Handbook.



Part B - Under reverse bias:

- Switch off the power supply and **adjust its output voltage to 12V**.
- Turn the zener diode carrier through 180° to connect it in reverse bias.
- Turn the variable resistor knob fully anticlockwise again.
- Switch on the power supply and increase the voltage applied to the zener by turning the variable resistor knob **slowly** clockwise. Watch the ammeter reading as you do so.
- Stop increasing the voltage when you observe a current flowing through the diode.
- Write down the voltage reading at which this happens in the Student Handbook.

WORKSHEETS

Worksheet 2 - The Zener Diode

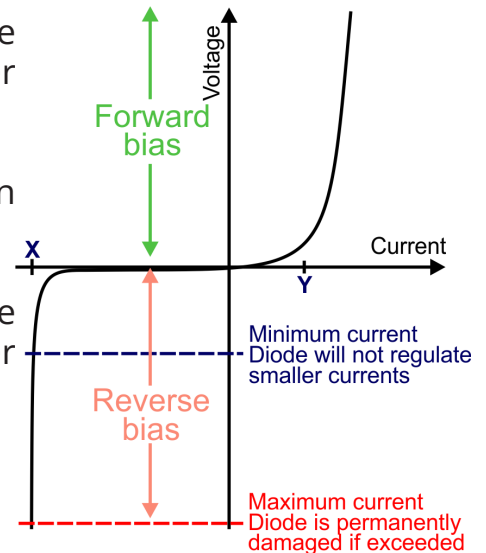
So What?

The behaviour of a typical zener diode is shown in the graph. The voltage labelled 'X' is known as the zener voltage, V_z .

Compare the behaviour you observed in the investigation with that shown in the graph.

Devices are available with a range of zener voltages. The table shows zener voltages for part of the BZX55 zener diode series. (These are temperature dependent.)

2.4V	2.7V	3.0V	3.3V	3.6V	3.9V
4.3V	4.7V	5.1V	5.6V	6.2V	6.8V
7.5V	8.2V	9.1V	10V	11V	12V



You may recognise the values as those used in the E24 resistor series.

Another important parameter is the power rating, P_D , of the zener diode. The BZX55 series has a power rating of 500mW. This can be used to calculate the maximum permissible current, using the formula: $I_{max} = P_D / V_z$.

For example, a 1N5913B zener diode has a zener voltage of 3.3V and a steady-state power rating of 1W. This means that it can sustain a reverse current of $1 / 3.3 = 303\text{mA}$.

Typical application - a reference voltage source:

As the graph shows, the voltage across a zener diode in reverse breakdown changes very little as the current changes. This makes it very useful as a constant voltage source in a number of applications, such as ADCs (analogue-to-digital converters) and DACs (digital-to-analogue converters).

Here is the analysis for the simple reference voltage source in the circuit diagram below:

Reference voltage = 12V (set by the zener voltage of the diode.) Supply voltage, V_s , is shared between the zener diode and resistor, R . Ignoring any current drawn from the voltage source output, the same current, I , flows through both.

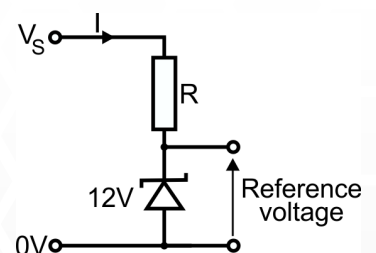
Suppose that: $V_s = 15\text{V}$, $R = 300\Omega$

The voltage across resistor $R = V_s - V_z = 15 - 12 = 3\text{V}$.

Applying Ohm's law to the resistor, current $I = V / R = 3 / 300 = 0.01\text{A} = 10\text{mA}$.

Power dissipated in the zener diode = $V_z \times I = 12 \times 10 = 120\text{mW}$.

Power dissipated in the resistor = $V \times I = 3 \times 10 = 30\text{mW}$.



WORKSHEETS

Worksheet 3 - On/Off Control BJT Switch



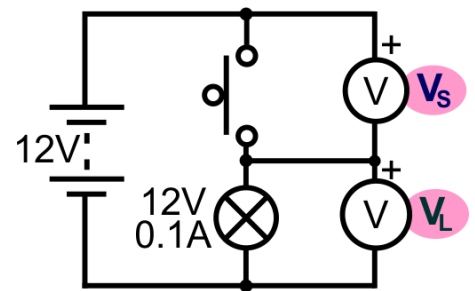
The module begins by looking at on/off control of electrical devices, switched using a variety of electronic components.

The first worksheet looks at the question: "What exactly is a switch?" It compares the behaviour of an electronic switch with that of a mechanical switch.

Over to you:

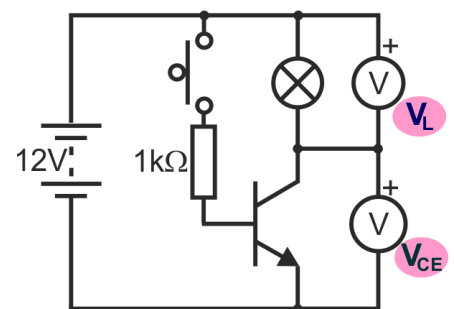
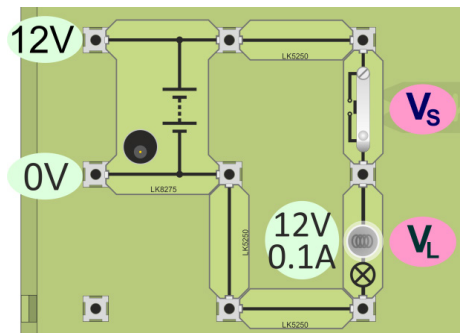
A switch is a two-state device. The states are called open (or off) and closed (or on).

- Build the first circuit, where a push-switch controls a lamp.
- Set the DC power supply to output 12V.
- Measure the voltage, V_S , across the switch:
- When the switch is open;
- When it is closed.



Notice the behaviour of the lamp as you operate the switch.

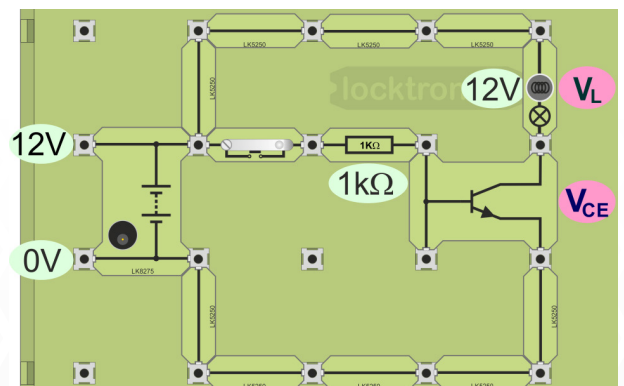
- Move the voltmeter down to measure the voltage, V_L , across the lamp, with the switch open and then closed.
- Write your results in the table given in the Student Handbook.
- Build the second circuit, where a transistor controls the lamp.



With the switch closed, a small base current flows, causing a much larger collector current through the lamp.

- Using a 12V DC supply, measure voltages:
- V_L , across the lamp;
- V_{CE} , across the transistor;

when the switch is open and when closed.



- Notice the effect of the switch on the lamp.
- Write your results in the table given in the Student Handbook.

WORKSHEETS

Worksheet 3 - On/Off Control BJT Switch

So What?

- Look at the results for the second part of the investigation.
- Add together V_{CE} and V_L . What do you notice?
- What do you expect, bearing in mind that the transistor and lamp form a voltage divider across the power supply?
- The behaviour is the same as for the mechanical switch. The transistor takes virtually all the supply voltage, or takes none. It is **saturated**, meaning that the collector-emitter voltage, V_{CE} , is either as high as it can be, (roughly the supply voltage - the 'off' state) or as low as it can be, (very close to 0V - the 'on' state).

A challenge or two:

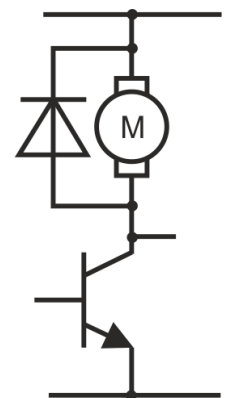
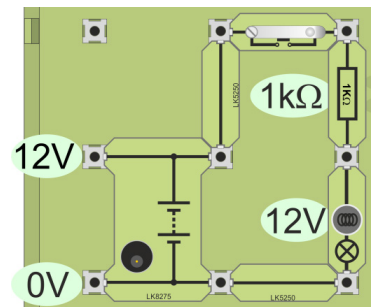
- To see the effect of the transistor, remove it! Connect the lamp directly to the switch and resistor, as shown opposite. The current is too small to light the lamp!

(You could remove the $1k\Omega$ resistor. The lamp then lights perfectly well. However, a transistor switch is often used with a sensor. For example, a light sensor could be used to switch on a lamp when it gets dark. Some sensors have a high resistance (represented by the $1k\Omega$ resistor in this case,) and will not operate output devices without the help of a transistor.)

- Modify the transistor circuit so that the lamp remains **on** when the switch is open and goes **off** when it is closed. (Hint - change the position of the switch.)
- Modify the circuit so that the switch controls a motor instead of the lamp. (You will need to add a diode in reverse parallel with the motor to protect the transistor as the motor is turned off - see the diagram opposite.)
- Modify the circuit so that the switch controls both the motor and the lamp.

(The diode is needed because the motor is an electromagnetic device:-

- The motor rotates because current flowing in its coil creates a strong magnetic field.
- When the current stops, the magnetic field collapses through the coil and generates a large voltage in the opposite direction, ('back-emf').
- This can damage the transistor.
- The power supply sees the diode in reverse bias.
- It essentially does nothing when the motor is rotating.
- The 'back-emf', however, sees the diode as forward biased, and conducts freely.
- This clamps the voltage drop across the diode to 0.7V.
- The transistor sees this as 12.7V, which poses no risk to the transistor.



WORKSHEETS

Worksheet 4 - On/Off Control - MOSFET Switch

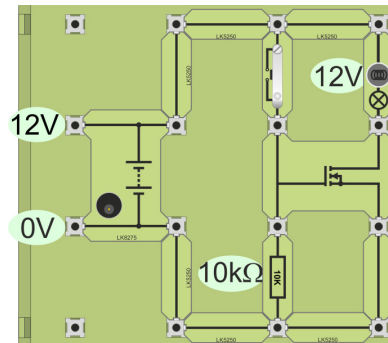
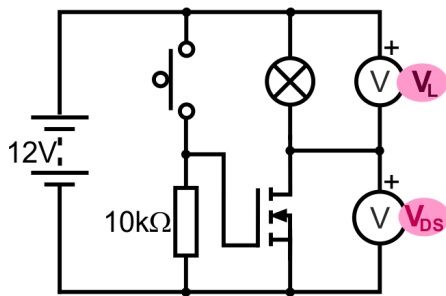


The BJT switch is a current-controlled device. The collector-emitter resistance depends on the base current.

A problem - some subsystems cannot deliver sufficient current to switch on the BJT. The MOSFET switch, the focus of this worksheet, may then be a more suitable control device.

Over to you:

- Build the circuit shown below and set the DC power supply to output 12V.
- Measure voltages V_L , across the lamp and V_{DS} , between drain and source of the MOSFET when the switch is open and when closed.
- Write your results in the table in the Student Handbook.



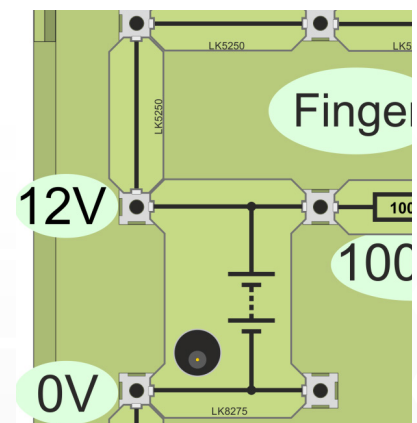
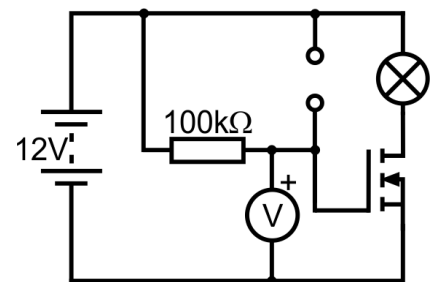
The next circuit illustrates the principle of the touch switch, a common MOSFET application.

- Build the second circuit .
- The DC power supply is set to output 12V, as before.
- Switch on. At this stage, the lamp should be off. If it is glowing, swap the resistor for a bigger value. (Device characteristics vary slightly between MOSFETs.)
- Check the voltage on the gate terminal - it should be between 2.2V and 2.4V.
- Press your fingers in the gap between the posts on the Locktronics board. (It works even better if you dampen your fingers first!)

This is safe - it is a low-voltage circuit.

Do not try this in high-voltage circuits!

- Observe the behaviour of the lamp and voltmeter as you do so.
- Answer the question posed in the Student Handbook.



WORKSHEETS

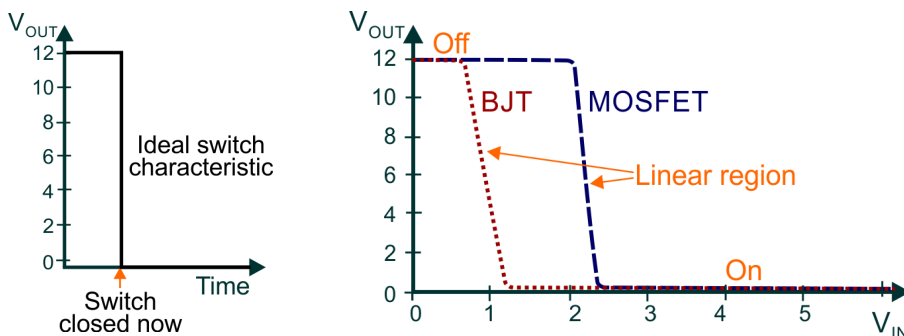
Worksheet 4 - On/Off Control - MOSFET Switch

So What?

The enhancement-mode MOSFET:

- It is "Off" when the gate bias voltage is zero.
- A drain current flows only when the gate voltage (V_{GS}) is greater than zero.
- This voltage pulls 'free' charge carriers (electrons or holes, depending on the type) into the channel between drain and source, reducing the drain-source resistance, r_{DS} .
- As a result, a current, I_D , flows between the drain and the source.
- Increasing the gate voltage increases the number of 'free' carriers and the drain current.
- Eventually, the MOSFET 'saturates' and drain-source resistance reaches its lowest value, known as $r_{DS(on)}$.

The MOSFET transfer characteristic (showing how the output depends on the input,) is similar to that of the BJT transistor, with one major difference - the linear region is very small, making it very unlikely that the MOSFET will operate in this region, as shown below.



The exact voltages at which 'Off' ends and 'On' begins depend on the device itself. The above characteristics are generalised and illustrate the difference between the BJT and MOSFET, used as switches.

Switching:

Electrical power P is given by the formula: $P = I \times V$

The danger for semiconducting switching devices is that they overheat during switching.

- When switched **off**, the current I is zero and so the power dissipated in them is zero.
- When switched **on**, the voltage V is (ideally) zero and so the power dissipated is zero.

However, while the device is turning on or off, (passing through the linear region,) there is a current and the voltage across it is not zero. The power dissipated can then be appreciable. The solution is very fast switching from one state to the other.

The BJT is not good at this. For high currents and voltages (i.e. high power,) transistors do not make good switching devices. The smaller linear region, and faster switching time of the MOSFET make it more suitable as a switch, though a heat-sink may be needed in high power applications.

WORKSHEETS

Worksheet 5 - On/Off Control - Thyristor Switch



Thyristors are designed to switch high currents and voltages and to do so very rapidly.

They are self-latching - once turned on, by a sufficiently large pulse of current flowing into the gate, they stay on, as long as:

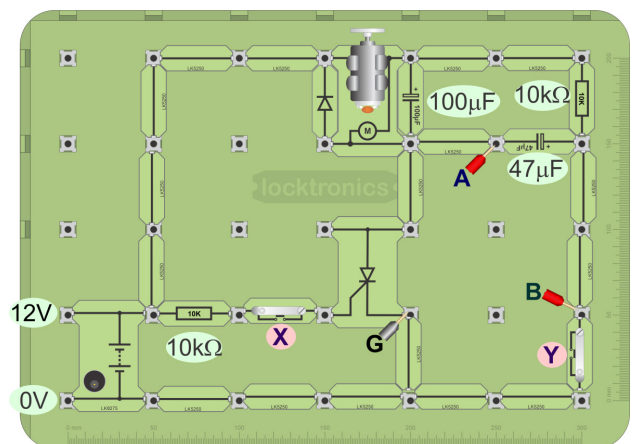
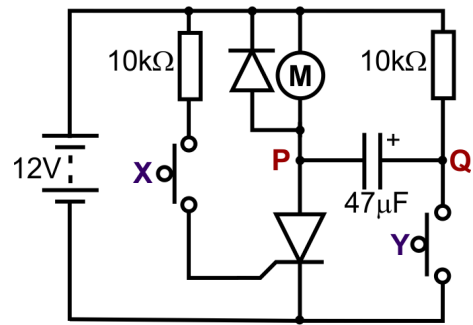
- It is forward-biased – anode more positive than cathode;
- A sufficiently large current flows from anode to cathode.

They make superb high-power switching devices because they move extremely quickly from the forward-blocking state, (forward-biased, but **not** conducting,) into the conducting state. As a result, they dissipate very little power in the process.

In some applications, they operate with AC currents. Here, the focus is on on/off control in a DC circuit.

Over to you:

- Build the circuit shown opposite, which includes:
- A 'flywheel diode' to prevent damage to the thyristor when the motor switches off;
- A $100\mu\text{F}$ capacitor to reduce noise which can prevent the thyristor latching on (not shown in the circuit diagram, - 'officially' it is not needed.)
- A $10\text{k}\Omega$ resistor to protect the gate from excessive current.
- Set the power supply to output 12VDC .
- Press and release switch X. Notice what happens.
- Press and release switch Y. Again, notice what happens. Record all observations in the Student Handbook.
- Set up a Picoscope to monitor:
- The voltage across the thyristor, (from points A to G);
- The voltage across switch Y, (from point B to G).
- Press and release switch X to turn on the thyristor and then switch Y to turn it off.
- Repeat this until you have a good trace showing the effect of switch Y.
- Save the resulting file for your records, or print out the trace.
- Answer the questions raised in the Student Handbook.



WORKSHEETS

Worksheet 5 - On/Off Control - Thyristor Switch

So What?

When switch **X** is closed, a current flows into the gate. The thyristor then switches on if:

- The current is bigger than the **minimum gate current**, I_{GT} , (typically $\sim 1 \text{ mA}$);
- **And** the voltage between gate and cathode, V_G , exceeds the **minimum gate voltage**, V_{GT} , (typically $\sim 0.8\text{V}$),

The thyristor then turns on and latches. The anode current continues to flow through the load even when switch **X** is opened again, provided this current does not drop below a value, called the **holding current**, I_H , typically $\sim 10\text{mA}$.

When conducting, a residual voltage drop of $\sim 1\text{V}$ between anode and cathode means that there is still some power dissipation. The thyristor may have to be cooled by a heat sink.

It behaves like a self-latching relay. Like the electromagnetic relay, it is capable of handling high currents. Unlike the relay, there are no moving parts to wear out through friction, and switching takes place a thousand times faster.

The method of switching off the thyristor used here is known as '**capacitor commutation**'.

Capacitor commutation:

Once in conduction, the thyristor cannot be turned off by signals applied to the gate. (In other devices, such as the GTO, gate-turn-off, thyristor, this is not true.)

The thyristor turns **off** only when:

- The anode-cathode current falls below the holding current threshold;
- Or the device is reverse-biased – the anode being less positive than the cathode.

The usual way to switch it off in a DC circuit is to use **capacitor commutation**.

When switched **off**:

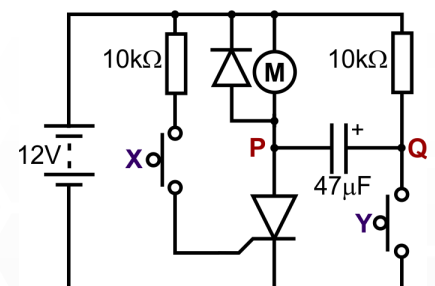
- The full supply voltage, 12V , sits across the thyristor and so point **P** sits at $+12\text{V}$. (The voltage drop across the load is zero and no current flows.)
- The voltage at point **Q** = $+12\text{V}$ as switch **Y** is open.

Closing switch **X**:

- Sends a current into the gate, switching **on** the thyristor;
- The voltage at **P** drops to $\sim 0\text{V}$ leaving the supply voltage, 12V , across the load, and a current flowing through it. (Switch **X** can be released - the thyristor is latched on.)
- The voltage at **Q** = $+12\text{V}$ still.

The left-hand side, (**P**), of the capacitor sits at 0V , and the right-hand side, (**Q**), at $+12\text{V}$.

Put another way, **Q** is 12V higher than **P**.



WORKSHEETS

Worksheet 5 - On/Off Control - Thyristor Switch

So What?

Capacitor commutation

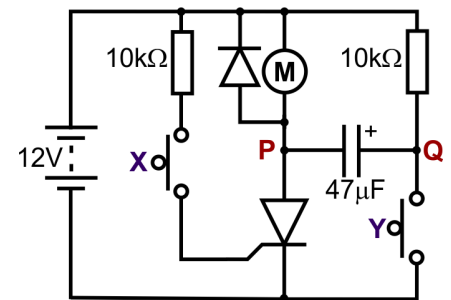
To switch off the thyristor, press switch Y:

- The voltage at Q falls **suddenly** to 0V.

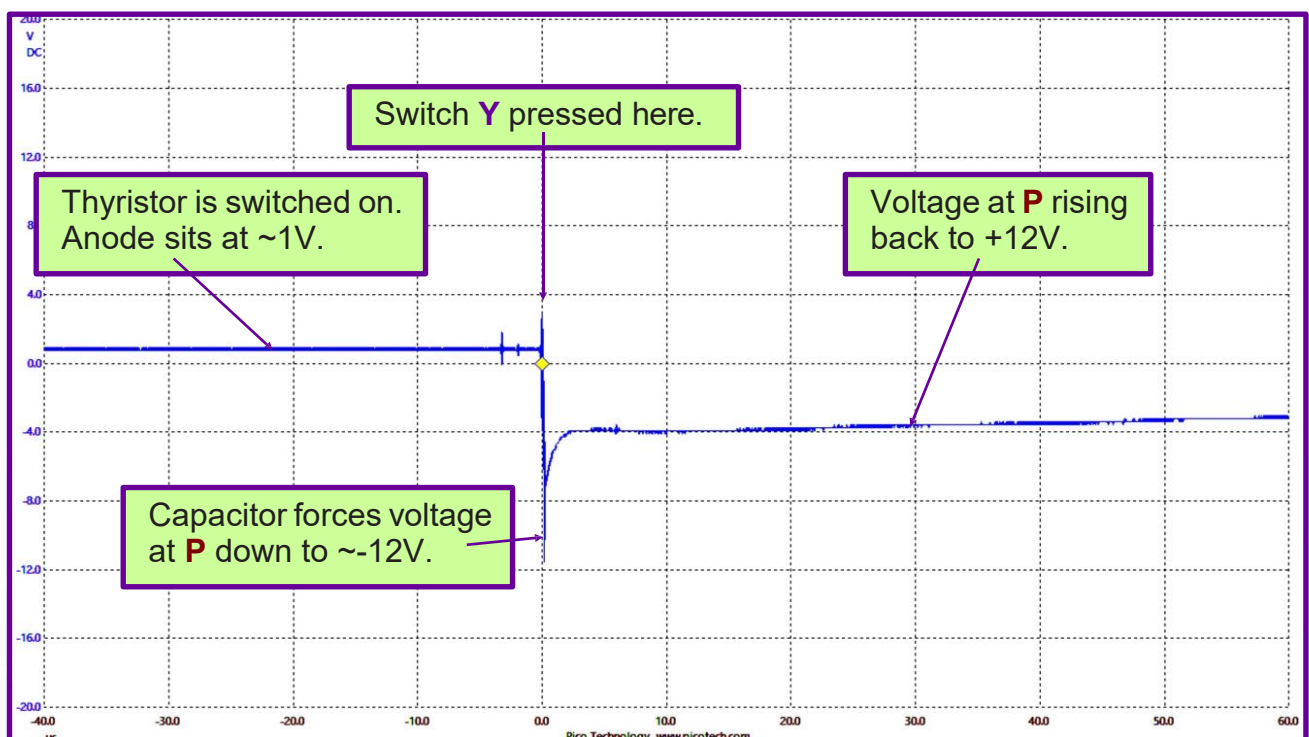
The voltage drop across a capacitor cannot change until charge flows, i.e. until there is a current.

As a result, a sudden voltage change on one terminal causes an equal voltage change on the other, as there is no time for charge to flow.

- Q must still be 12V higher than P. When the voltage at Q dropped from 12V to 0V, the capacitor forced the voltage at P down by the same amount, from 0V to -12V. The anode, connected to P, is at ~ -12V, but the cathode is connected to 0V. The thyristor is reverse-biased and so switches off.
- A large current now flows through the load onto the left-hand plate of the capacitor, causing the voltage at P to rise quickly to +12V. Similarly, when Y is released, current through the 10kΩ pull-up resistor returns the voltage at Q to +12V.



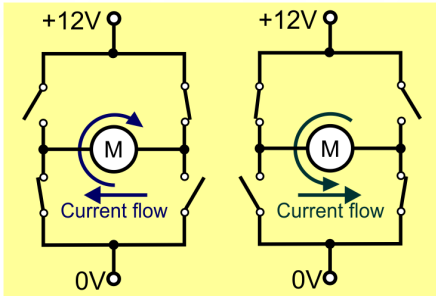
The following trace shows the changes in the voltage at P when switch B is pressed:



WORKSHEETS

Worksheet 6 - On/Off/Direction Control - H-Bridge

The H-bridge is a system of switches which control the direction of rotation of a motor by controlling the direction of current flow through it.



The diagram shows how four mechanical switches could do this, though the worksheet uses four MOSFET switches.

The shape of the central part of the diagram puts the 'H' in 'H' bridge!

One problem - the power supply will be short-circuited if the wrong pair of switches is closed! The following investigation uses a changeover switch to avoid this.

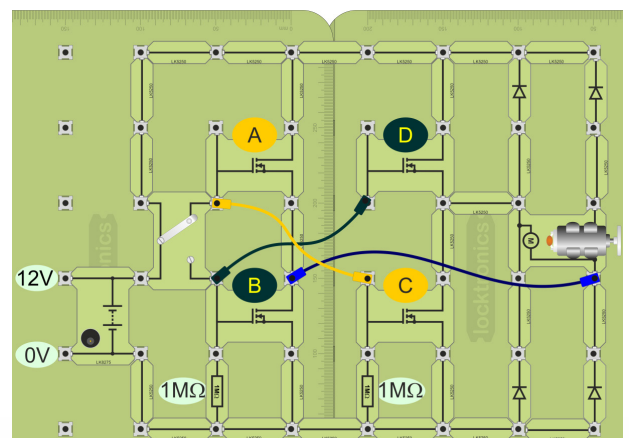
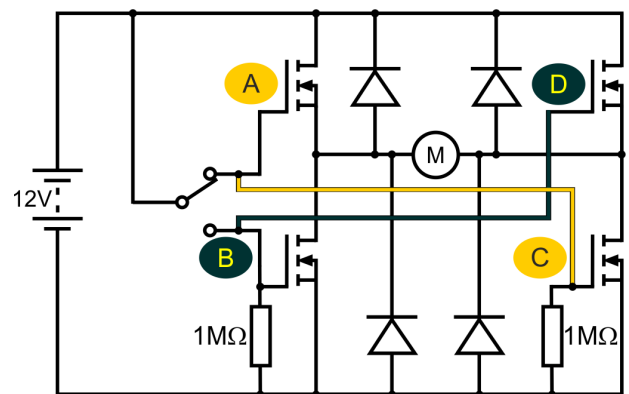
Over to you:

- Build the circuit shown opposite.

Notice the yellow wire linking the gates of MOSFETs **A** and **C** and the green wire linking the gates of MOSFETs **B** and **D**.

These ensure that:

- All MOSFET gates are held at a low voltage by $1M\Omega$ resistors;
- Either:
MOSFETs **A** and **C** are on,
or
MOSFETs **B** and **D** are on,
depending on the changeover switch position.



- Set the DC power supply to 12V and switch it on.
- Notice the effect of moving the changeover switch to:
 - The upper position;
 - The lower position;
 - Mid-way between them.
- For each position, measure the voltage on the left end of the motor, (drain of **C**) and on the right end (drain of **B**).
- Record these in the Student Handbook and answer the questions.

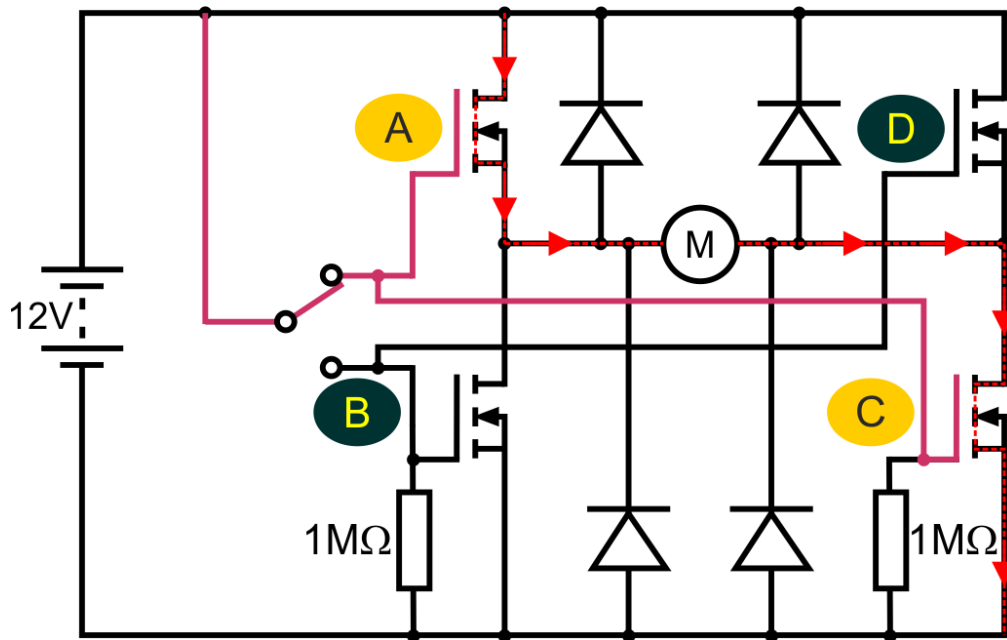
NB: don't forget to wire the blue lead between the drain of B and the motor.

WORKSHEETS

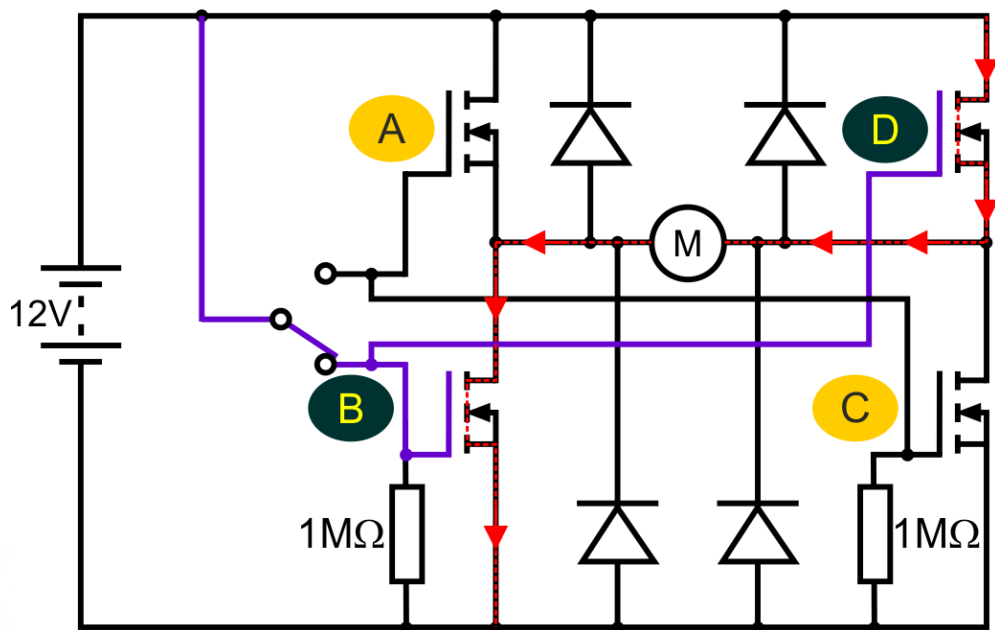
Worksheet 6 - On/Off/Direction Control - H-Bridge

So What?

The diagrams show that the current direction through the motor reverses when the changeover switch moves to switch on the other pair of MOSFETS.



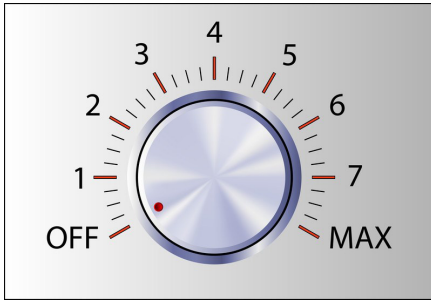
MOSFETs **A** and **C** are 'on' and current flows from left to right through the motor.



MOSFETs **B** and **D** are 'on' and current flows from right to left through the motor.

WORKSHEETS

Worksheet 7 - Motor Control - BJT Emitter Follower



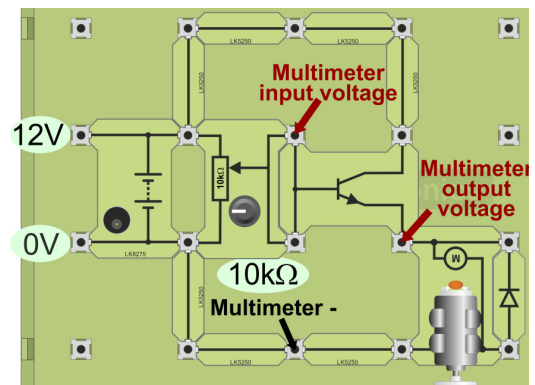
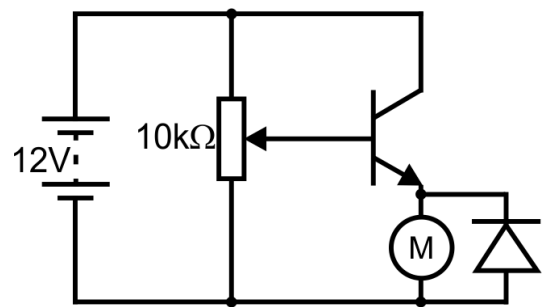
The circuits studied so far offer 'on/off' control. Sometimes, that is not enough. We might want to speed up or slow down a motor, increase or decrease the brightness of a lamp etc. Then we need graduated control.

One way to achieve this is with the BJT emitter follower circuit, which uses a configuration, called 'common-collector'. Here, the collector is connected directly to the positive power supply rail, The base terminal is the input, as before, but the output is taken from the emitter.

The emitter follower delivers both high voltage and current to the load. For electromagnetic loads, such as a motor, it is best to incorporate a flywheel diode to protect the transistor from back e.m.f. when the current switches off suddenly.

Over to you:

- Build the circuit shown opposite.
- Use the 'pot' to vary the input voltage and watch the behaviour of the motor as you do so. This circuit allows fine control of motor speed.
- Use a multimeter to measure the input voltage, V_{IN} .
- Adjust the 'pot' to give an input voltage of 0V.
- Measure the corresponding output voltage, V_{OUT} .
- Do the same for inputs of:
 - 1.0V;
 - 2.0V;
 - 3.0V;
 - 4.0V;
 - 5.0V.
- Each time, measure the corresponding output voltage, V_{OUT} .
- Record the measurements in the table given in the Student Handbook. Carry out the tasks described in it.



WORKSHEETS

Worksheet 7 - Motor Control - BJT Emitter Follower

So What?

This circuit is useful as an interface between an input device that can supply only a small current and a subsystem that draws a much larger current.

Even though the voltage gain is around unity, the circuit has a high power gain (= current gain x voltage gain) because of its high current gain.

Interpreting the results:

- When the input voltage V_{IN} is greater than $\sim 0.7V$, the transistor starts to conduct.
- As a result, a voltage drop of $\sim 0.7V$ is created between base and emitter.
- The remainder of V_{IN} is dropped across the motor, as output voltage V_{OUT} .
- Hence, the emitter follower relationship:

$$V_{OUT} = V_{IN} - 0.7$$

Voltage gain:

$$\begin{aligned}\text{Voltage gain} &= V_{OUT} / V_{IN} \\ &= \sim 1\end{aligned}$$

Current gain:

Output current through load = emitter current I_E

Input current = I_B

$$\begin{aligned}\text{Current gain} &= \text{output current} / \text{input current} \\ &= I_E / I_B\end{aligned}$$

From Kirchhoff's current law:

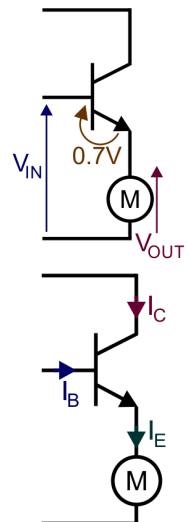
$$I_E = I_C + I_B$$

and

$$I_C \gg I_B$$

Hence

$$\text{current gain} = \sim I_C / I_B = \sim h_{FE} \text{ (the current gain of the transistor.)}$$



Sample measurements:

The following measurements were taken from the circuit:

Input voltage, V_{IN}	3.0V
Output voltage, V_{OUT}	2.5V
Input current, I_B	0.8mA
Output current I_C	108mA

Using them gives:

$$\text{Voltage gain} = 0.8$$

$$\text{Current gain} = 135$$

Hence

$$\text{Power gain} = 108$$

Challenge:

Repeat the measurements for an input voltage of 5.0V.

Is there any effect on the power gain?

WORKSHEETS

Worksheet 8 - Motor Control - Darlington Driver



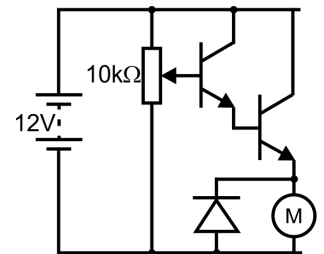
Sometimes, one transistor just isn't enough!

The emitter follower demands a sizeable input current which some subsystems, some logic gates, for example, just can't deliver.

One solution is to couple two transistors together in an arrangement known as a darlington pair - rather like on a railway where they couple together two engines when there is a heavy load to pull!

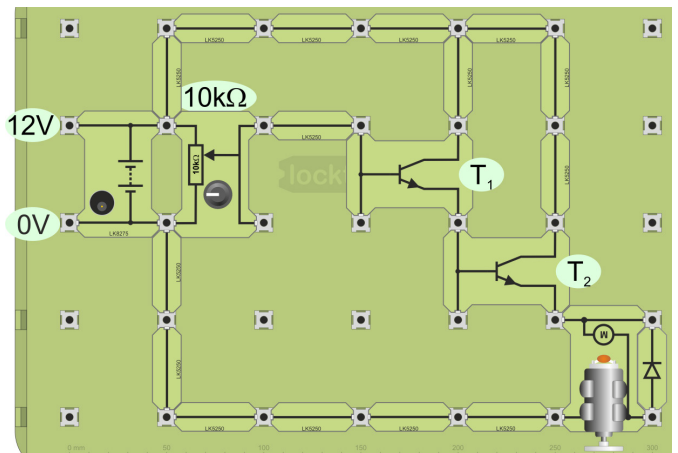
Over to you:

- Build the circuit shown opposite. The procedure is identical to that used in worksheet 7.
- Use the 'pot' to vary the input voltage, watching the effect of the motor.
- Connect a multimeter to measure the input voltage, as before.
- Adjust the 'pot' to give an input voltage of 0V and measure the corresponding output voltage.



If you are unsure about how to take these measurements, look back at the previous worksheet. They are taken from the same points.

- Make the same measurements for inputs of 1.0V, 2.0V, 3.0V, 4.0V, 5.0V and 6.0V.
- Record them in the Student Handbook.



To see the advantage of this arrangement over that used in worksheet 7:

- Set the input voltage to 5.0V.
- Measure the input current (base current in the first transistor, T_1).
- Measure the output current from transistor T_2 , (current through the motor and back to the power supply).
- Record them in the Student Handbook.
- Use them to calculate the power gain of the circuit.

WORKSHEETS

Worksheet 8 - Motor Control - Darlington Driver

So What?

The input voltage fixes the input (base) current of the first transistor, which then controls a much larger collector (and emitter) current in that transistor. This becomes the base current of the second transistor, controlling an even larger output (collector) current.

The transistors usually have different properties. The first (T_1) has a high current gain but low power rating. The second (T_2) has a higher power rating and a lower current gain.

The following sample measurements were obtained:
Using them gives:

Voltage gain = 0.6
Current gain = 1150
Hence Power gain = 690

Input voltage, V_{IN}	3.0V
Output voltage, V_{OUT}	1.9V
Input current, I_B	0.08mA
Output current I_C	92mA

Advantages of the Darlington pair follower:

- Very high current gain (= gain of T_1 x gain of T_2);
- Very high input impedance.

(For a given output, the input current is tiny, as if the subsystem had a huge impedance.)

Disadvantages of the Darlington pair follower:

- Higher overall voltage drop between input and output (~1.4V compared to ~0.7V for the emitter follower);
- Higher saturation voltage, when switched on fully, resulting in higher power dissipation.

Challenge:

To demonstrate the ability of the darlington driver to work off extremely low inputs, set up the circuit shown opposite, which uses a phototransistor as a light sensor.

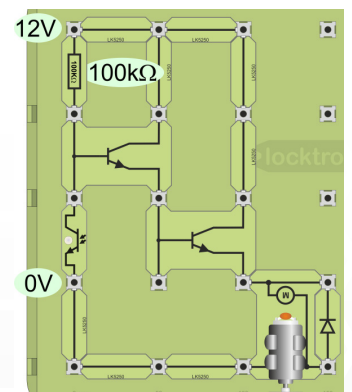
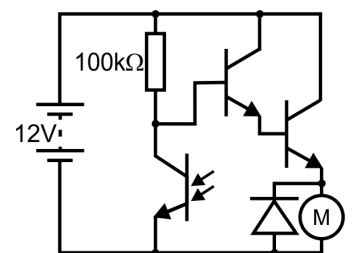
Notice what happens when you cover the phototransistor window (You may need to adjust the size of the resistor to match current light conditions and component tolerances!)

As the light level drops:

- The resistance of the sensor increases;
- The base voltage of the first transistor increases;
- The base current to the first transistor increases;
- The current through the motor increases;
- The motor spins faster.

The 100k Ω resistor in the sensing subsystem means that the current available to the darlington driver is tiny.

Determine the power gain of the darlington driver in bright and in dim light.



WORKSHEETS

Worksheet 9 - Motor Control - MOSFET Source Follower



Depending on the application, MOSFETs can offer significant advantages over BJTs, including:

- Higher input impedance - less current required to operate it;
- Smaller power loss - the effect of the residual resistance, $R_{DS(ON)}$, of the MOSFET is usually smaller than that of the BJT forward voltage drop V_{CE} ($\sim 0.3V$) when the devices are switched on;
- Faster switching - conduction by majority, not minority carriers;
- No tendency for thermal runaway.

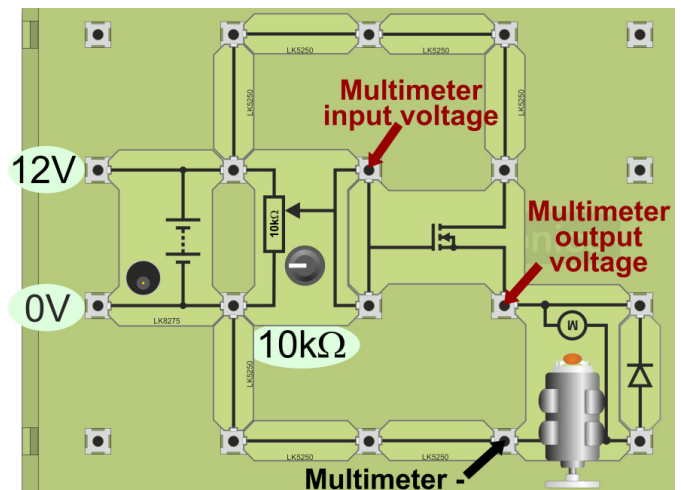
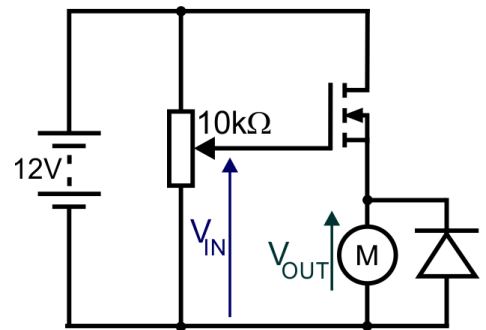
This worksheet examines the behaviour of the MOSFET common-drain amplifier, also called the 'source follower'.

Over to you:

The procedure mirrors that used to investigate the emitter follower in worksheet 6.

Source follower:

- Build the circuit shown opposite.
- Set the DC power supply to 12V.
- Use the 'pot' to vary the input voltage and watch the behaviour of the motor as you do so.
- Connect a multimeter to measure the input voltage, V_{IN} .
- Adjust the 'pot' to give an input voltage of 0V.
- Measure the corresponding output voltage, V_{OUT} .
- Do the same for inputs of:
 - 1.0V;
 - 2.0V;
 - 3.0V;
 - 4.0V;
 - 5.0V;
 - 6.0V.



- Each time, measure the corresponding output voltage, V_{OUT} .
- Record the measurements in the table given in the Student Handbook.
- Compare the behaviour of the emitter follower and source follower.

WORKSHEETS

Worksheet 9 - Motor Control - MOSFET Source Follower

So What?

As with the emitter follower, this circuit is a useful interface between an input subsystem that can supply only limited current and a subsystem that draws a high current.

- The output voltage follows the input voltage, but is about 2V lower.
- It has the advantage that the input impedance is huge, almost infinite.
- Its output impedance is low but not as low as that of the emitter follower.
- The current gain (output current/input current) is enormous, because the input current is so small. Although the voltage gain is less than unity, overall there is a big power gain.
- It provides a reasonably low output impedance to the following subsystem. A low output impedance means that the output voltage will not drop when a current is drawn by a load attached to it.
- The MOSFET is in saturation, so the current through the motor, and hence motor speed, is determined by the input (gate-source) voltage.

However, it has a higher input turn-on voltage than the BJT emitter follower, ~3V as opposed to ~0.7V.

Sample measurements:

The following measurements were taken from the circuit:

Input voltage, V_{IN}	5.0V
Output voltage, V_{OUT}	2.7V
Input current, I_B	0.1mA
Output current I_C	108mA

Using the same argument as for the emitter follower, these results give:

Voltage gain = 0.5

Current gain = 1080

Hence **Power gain = 540**

Challenge:

Repeat these measurements for an input voltage of 6.0V.

Once again, does this have any effect on the power gain?

WORKSHEETS

Worksheet 10 - Motor Control - PWM



Pulse-width modulation (PWM) offers not only motor speed control but also position control for servo motors, (used in a variety of applications, including industrial robots.)

PWM is a digital technique - the signal is either on or off.

Its advantages include:

- Superior energy efficiency, compared to analogue methods;
- Compatible with digital devices, such as microcontrollers.

One way to generate and control PWM uses a 555 timer IC.

Over to you:

- Build the circuit shown opposite. (The Locktronics 555 carrier incorporates some of the connections.)
- Set up a Picoscope to monitor the 555 output signal, (points **A** and **G**). Connect:
- The 'ground' terminal to the '0V' rail (at **G**);
- Channel **A** to the 555 output (pin 3).

Suitable Picoscope settings:

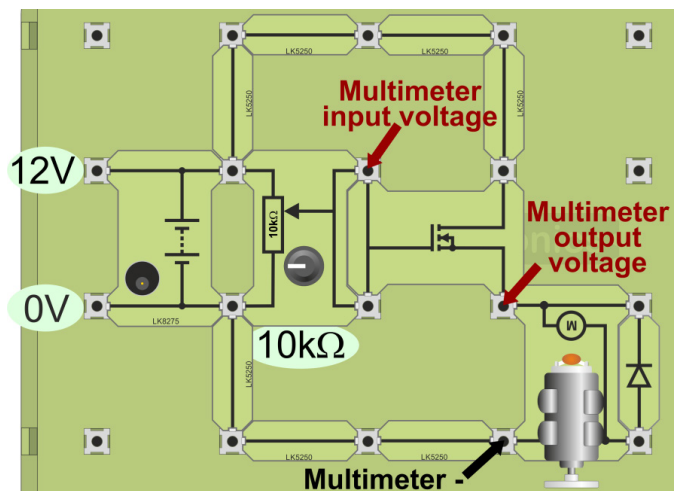
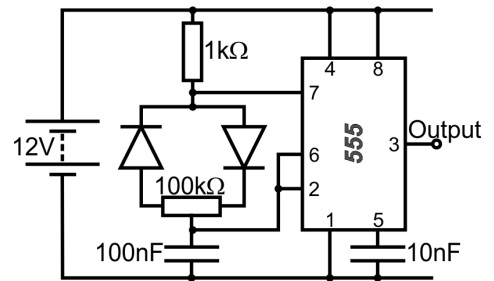
Input range: A	+/-20V DC
Collection time	10ms/div
Trigger mode	Auto
All other settings	Default values

- Adjust the 'pot'. Notice the effect on the signal.
- Turn the knob on the 'pot' fully clockwise (almost!) Save or print out the trace for your records.
- Then do the same with the knob turned (almost) fully anticlockwise.
- Answer the questions in the Student Handbook.

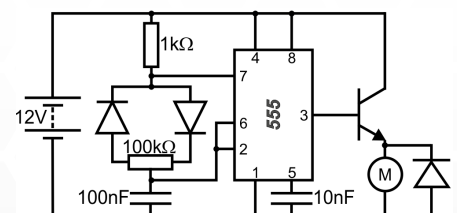
Challenge:

Use this system to control the speed of a motor, using the circuit shown below, which includes a BJT emitter follower to reduce the current drawn from the 555 timer IC.

- On a second baseboard, build the emitter follower and motor subsystems, using worksheet 7 as a guide.
- Check that you can control the speed of the motor using the 'pot'.



NB: power/gnd connections of 555 timer not shown in layout.



WORKSHEETS

Worksheet 10 - Motor Control - PWM

So What?

In pulse-width modulation, the output signal switches on and off rapidly and repeatedly.

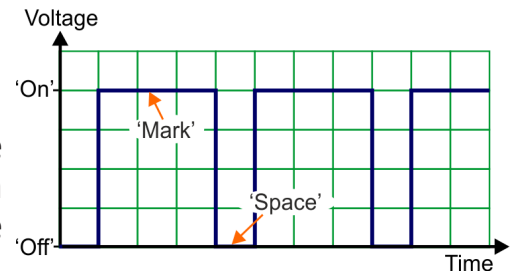
The 'mark' is the time for which it is 'on'.

The 'space' is the time for which it is 'off'.

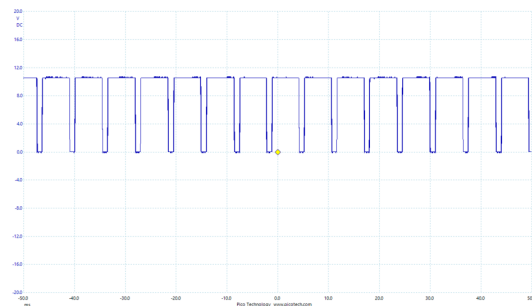
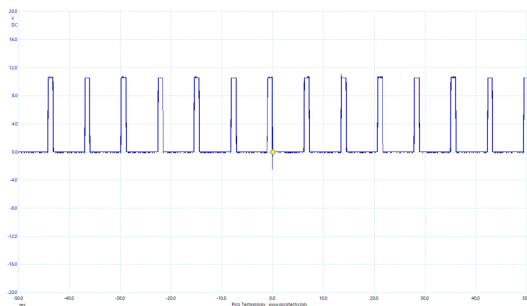
The signal shown has a mark-to-space ratio of 3:1.

The term 'duty cycle' is another measure of the same thing. It is defined as the percentage of time for which the output is 'on'. The signal shown has a duty cycle of 75%.

The motion of the electric motor is not affected providing the frequency at which switching occurs is sufficiently high. The inductance of the motor coil smooths out the current flowing in it. In addition, the inertia of the motor means that the motion is smooth.



The following traces were obtained from the PWM circuit, for different settings of the 'pot'. The signal on the left has a small mark:space (~1:7) - a duty cycle of ~15%. For the one on the right, the mark:space is ~7:1 - a duty cycle of ~83%.



Why is PWM energy-efficient?

The power **P** dissipated in a device is given by the formula:

$$P = I \times V$$

where **I** = current flowing through the device and **V** = voltage dropped across it.

In an ideal switch:

- When on, there is no voltage across it, i.e. **V** = 0 and so **P** = 0 - no energy wasted in it;
- When off, there is no current through it, i.e. **I** = 0 and so **P** = 0 - again no energy wasted.

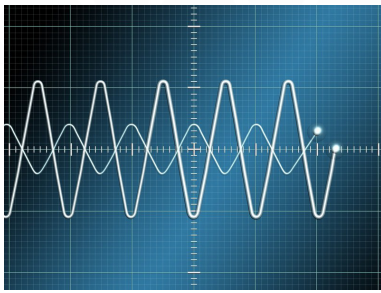
Providing the switching device moves rapidly from the 'off' state to the 'on' state, very little energy is wasted.

Challenge:

- Using the 100nF capacitor in the circuit, measure the time period for the signal.
- Hence calculate the frequency of the signal.
- Investigate the effect of changing the 100nF capacitor for other similar values.
- Record your conclusions in the Student Handbook.

WORKSHEETS

Worksheet 11 - Phase Control



The graduated control systems looked at so far use DC power. Where an AC power supply is used, another option becomes available - phase control, the focus of this worksheet.

This technique offers reliable and energy-efficient operation of power control devices such as thyristors and triacs.

Over to you:

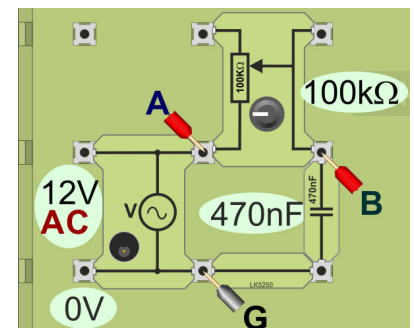
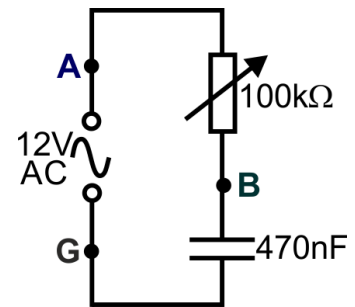
- Build the circuit shown opposite.

It uses the 12V AC power supply!

The 100kΩ 'pot' is set up as a variable resistor.

The non-electrolytic capacitor can be connected either way round.

- Set up a Picoscope to monitor the voltage across the AC supply, (points **A** and **G**) and the voltage across the capacitor, (points **B** and **G**):
- Connect one of the oscilloscope's 'ground' terminals to the '0V' rail (at **G**);
- Connect channel **A** to monitor the AC supply;
- Connect channel **B** to monitor the capacitor.
- Adjust the 'pot' and notice the effect on the signal on channel **B**, the voltage across the capacitor.
- With the 'pot' turned fully clockwise, save the resulting traces for your records, or print them out .
- Then do the same with the 'pot' turned fully anticlockwise.



Suitable Picoscope settings:

Input range: A	+/-20V DC
Collection time	10ms/div
Trigger mode	Auto
All other settings	Default values

Key to labels:

- G** - 'ground' connection for all readings.
A - connection for AC supply measurement.
B - connection for capacitor measurement.

Challenge:

- Investigate the effect of using different resistor and capacitor values.
- Complete the passage in the Student Handbook.

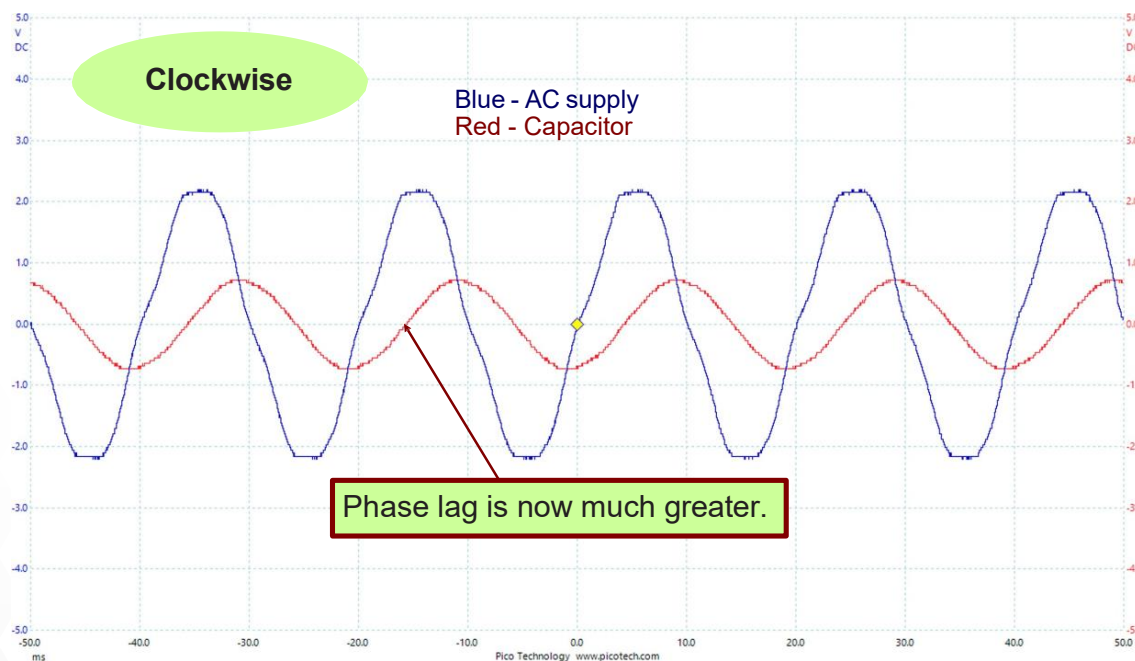
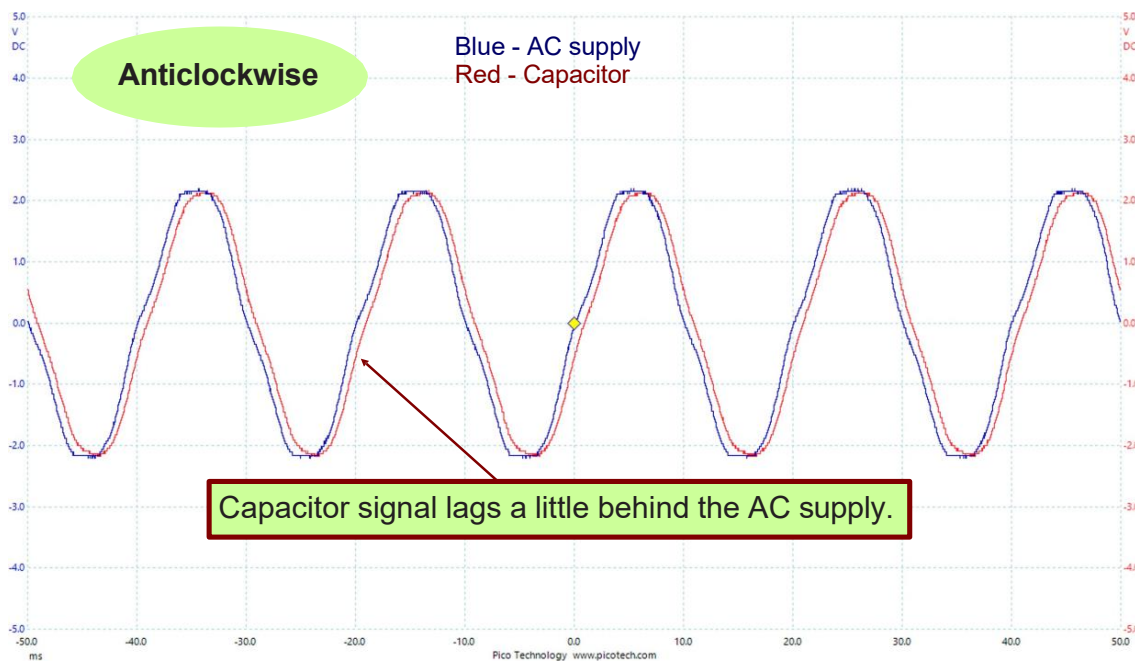
WORKSHEETS

Worksheet 11 - Phase Control

So What?

Interpreting the traces:

The following traces were obtained from the phase-control circuit. For clarity, the 'x10' setting was used on the probes. For the 'anticlockwise' trace, the 'pot' was moved slightly from the fully anticlockwise position. Otherwise, the capacitor and AC traces would overlap.



WORKSHEETS

Worksheet 12 - Lamp Control - Thyristor



The thyristor and its relative, the triac, are used in a wide variety of lamp dimmer circuits, in the home, in theatres and in public buildings such as sports stadia.

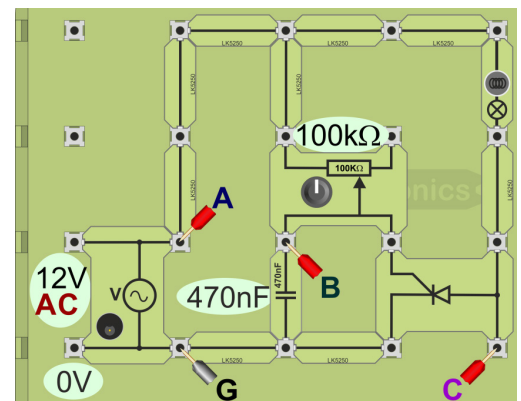
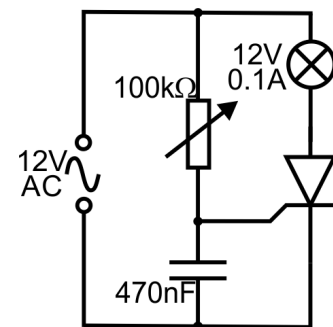
This worksheet demonstrates how to control the thyristor using 'phase control'.

Over to you:

- Build the circuit shown opposite.

As before:

- It uses the 12V AC power supply;
- The 100kΩ 'pot' is set up as a variable resistor;
- The capacitor can be connected either way round.
- Adjust the 'pot' and notice the effect on the brightness of the lamp.
- Set up a Picoscope to monitor:
- The voltage across the AC supply, (**A and G**) and across the capacitor, (**B and G**);
- The AC supply voltage (**A and G**) and the voltage across the thyristor (**C and G**).



One of the oscilloscope's 'ground' terminals is connected to the '0V' rail (at G).

- With the 'pot' turned fully clockwise, save the traces for your records, or print them out .
- Then do the same with the 'pot' turned fully anticlockwise.

Suitable Picoscope settings:

Input range: A	+/-20V DC
Collection time	10ms/div
Trigger mode	Auto
All other settings	Default values

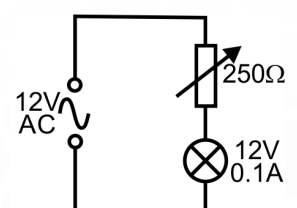
Key to labels:

- G - 'ground' connection for all readings.
- A - connection for AC supply measurement.
- B - connection for capacitor measurement.
- C - connection for thyristor measurement.

Challenge:

The simplest way to dim the lamp is to connect a variable resistor in series with it, as shown in the circuit diagram opposite.

- Build this circuit and measure the current flowing through the variable resistor for a dim glow, and then for full brightness.
- Calculate the power dissipated in the variable resistor for each.
- Record your results and answer the question in the Student Handbook .



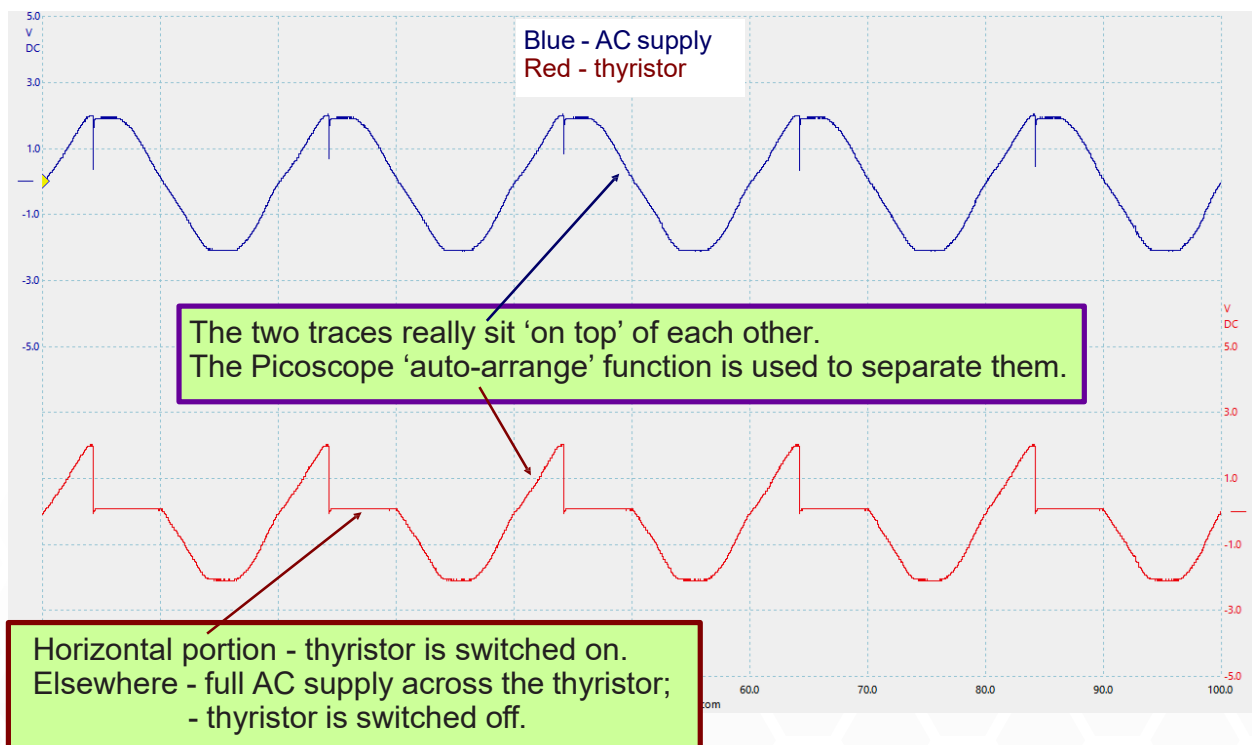
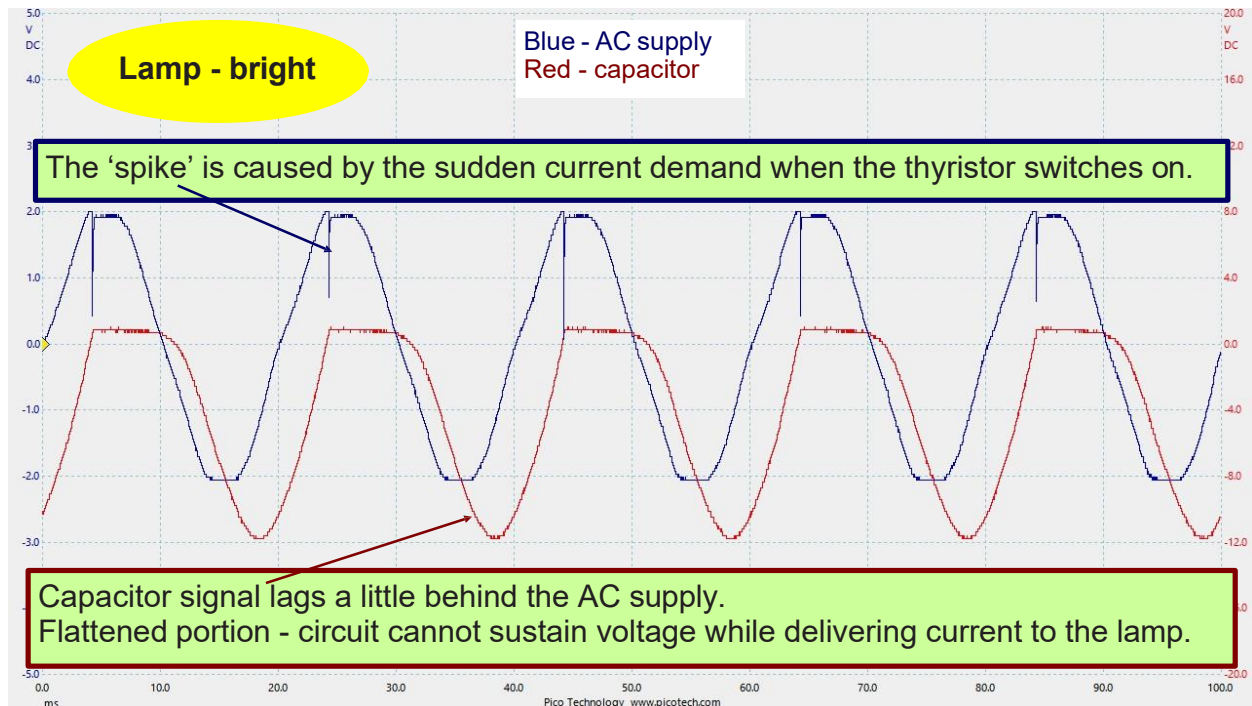
WORKSHEETS

Worksheet 12 - Lamp Control - Thyristor

So What?

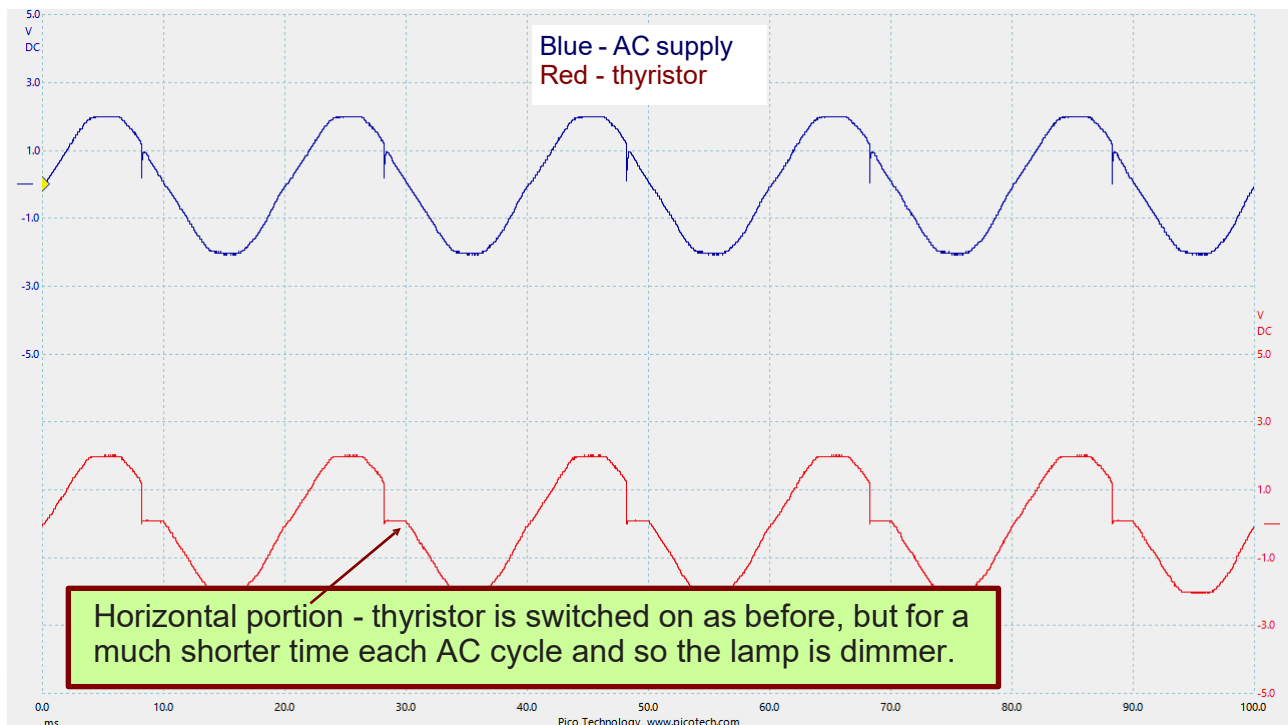
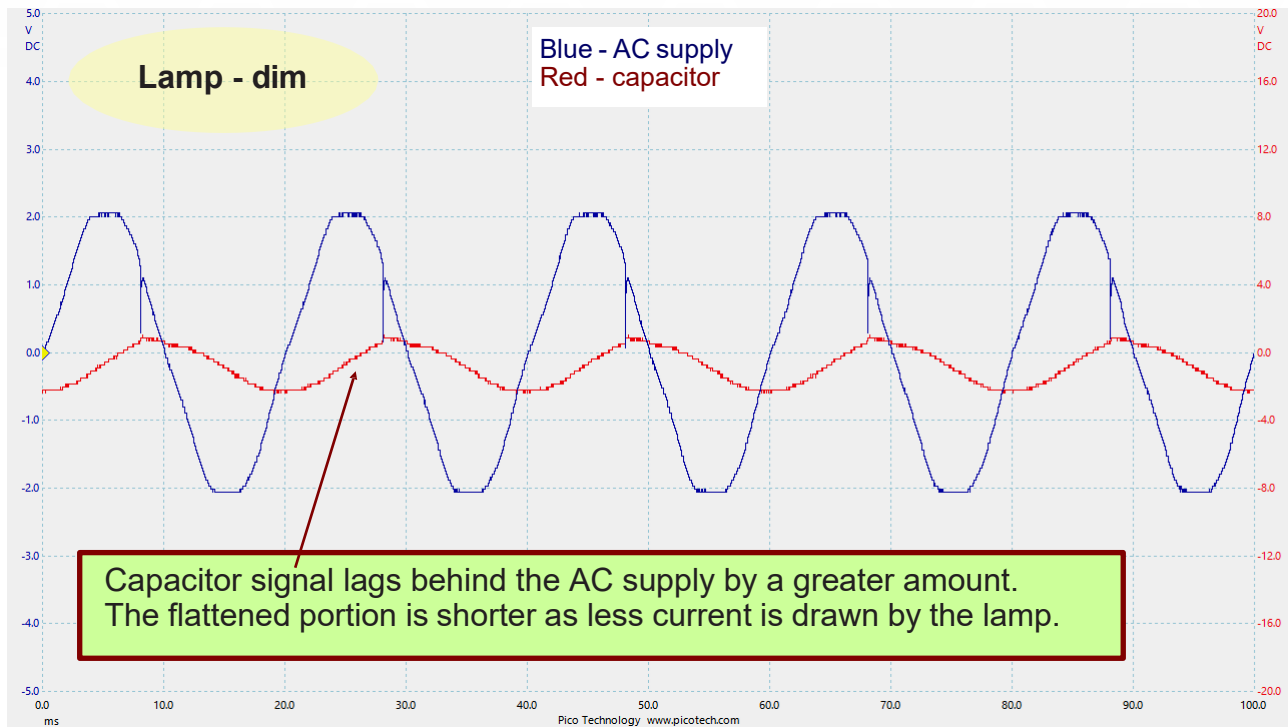
Interpreting the traces:

The following traces were obtained from the phase-control circuit. For clarity, the 'x10' setting was used on the probes.



WORKSHEETS

Worksheet 12 - Lamp Control - Thyristor



WORKSHEETS

Worksheet 13 - Lamp Control - Triac



The thyristor is also known as a silicon controlled rectifier (SCR). This highlights one aspect of its performance - it is a rectifier. Current can flow through it in one direction only. As a result, it is switched off for half of the time when powered by AC.

The triac allows current flow in both directions and so delivers more power to the load.

Over to you:

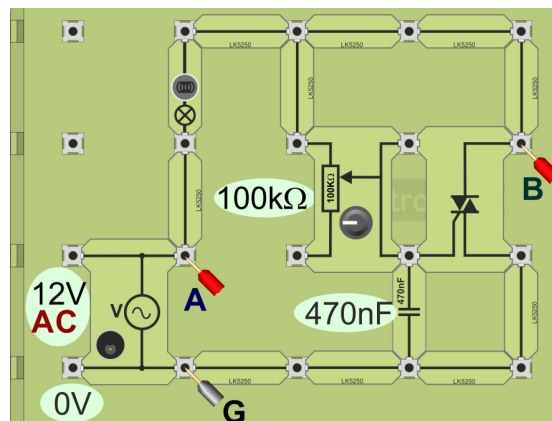
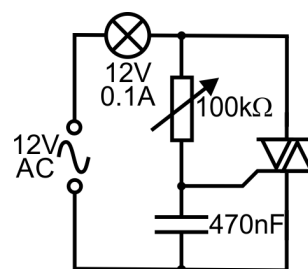
- Build the circuit shown opposite.

Look at the equivalent thyristor circuit (worksheet 10). There, the load, (the lamp,) is connected after the phase control network (the resistor and capacitor).

Here, it is before them. For most loads, it makes no difference which configuration is chosen.

As before:

- The circuit uses a 12V AC supply;
- The 'pot' is set up as a variable resistor;
- The capacitor can be connected either way round.
- Set up a Picoscope to monitor the voltage across the AC supply, (A and G) and across the capacitor, (B and G).



Suitable Picoscope settings:

Input range: A	+/-20V DC
Collection time	10ms/div
Trigger mode	Auto
All other settings	Default values

- Adjust the 'pot' and notice the effect on the brightness of the lamp.
- With the 'pot' turned fully clockwise, save the traces for your records, or print them out.
- Then do the same with the 'pot' turned fully anticlockwise.

Challenge:

- Swap the lamp with the connecting link just above the triac so that the load is after the phase control network. Does this make any difference?
- Investigate the effect of using different resistor and capacitor values.
- Answer the questions posed in the Student Handbook.

WORKSHEETS

Worksheet 13 - Lamp Control - Triac

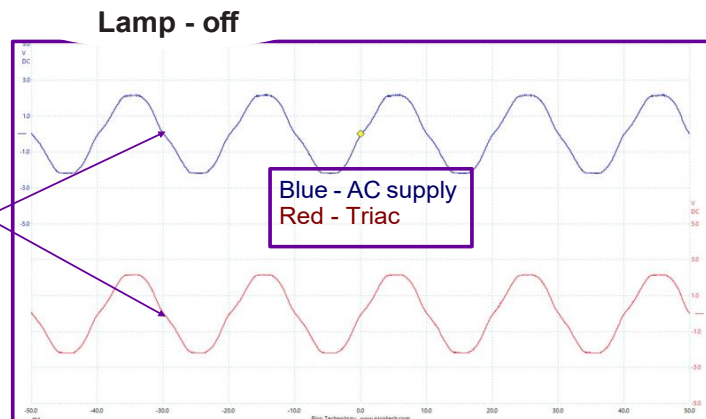
So What?

You probably noticed a sudden change in the brightness of the lamp as you adjusted the 'pot'. The cause can be seen in the sample Picoscope traces shown below.

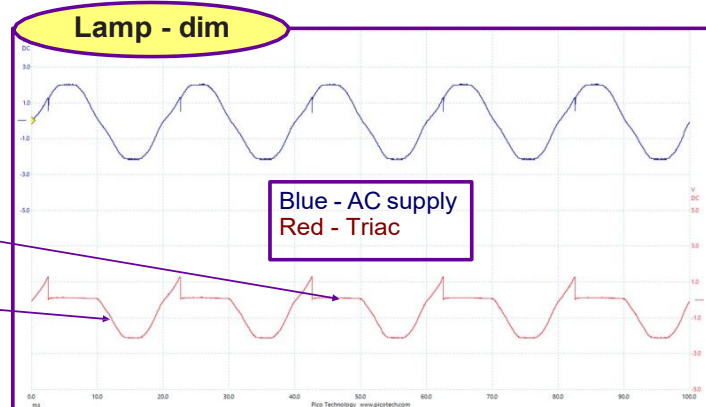
Interpreting the traces:

Once again, for clarity, the 'x10' setting was used on the probes and the Picoscope 'auto-arrange' function is used to separate the traces.

The full AC supply voltage appears across the triac. The voltage across the lamp is zero - the lamp does not light.



The triac switches on for part of the positive half-cycle (shown by the horizontal part of the trace) but is off throughout the negative half-cycle.



Once again, the 'spikes' show sudden current demand when the triac switches on.

The triac switches on for part of both the positive and negative half-cycles but not symmetrically.



WORKSHEETS

Worksheet 14 - The UJT Relaxation Oscillator

The UJT (unijunction transistor) has only one p-n junction, as its name suggests. However, it has three terminals, two called bases - base 1 and base 2, and one emitter.

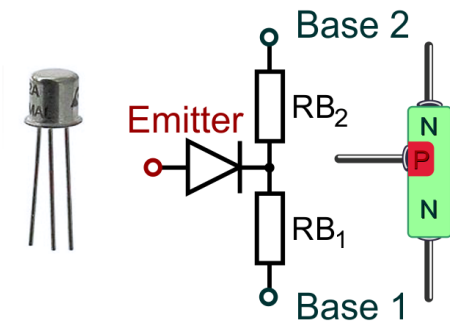
It has one aim in life - to oscillate.

It does so in a particular way, generating sharp 'spikes', ideal for triggering thyristors and triacs.

The diagram has details of the device. Its appearance is very similar to other, bipolar, transistors.

It consists of a bar of lightly doped n-type silicon, giving it a high resistance, typically a few kilohms. A small p-type area is created towards one end, effectively dividing up the device into two unequal resistors.

The equivalent circuit shows this arrangement.



Over to you:

- Build the circuit shown opposite, using a 12V DC power supply.

The 100kΩ 'pot' is set up as a variable resistor. The capacitor is non-electrolytic and so can be connected either way round.

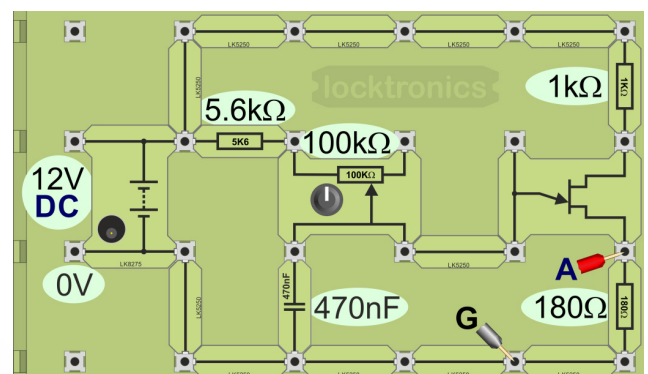
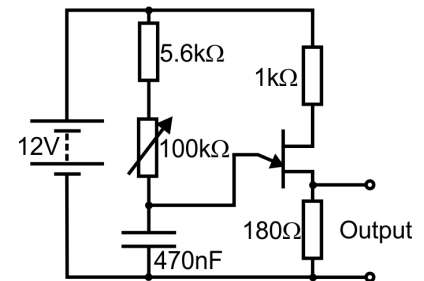
- Set up a Picoscope to monitor the signal across the 180Ω resistor, (A and G), with the 'ground' terminal connected to the '0V' rail (at G).

Suitable Picoscope settings:

Input range: A	+/-10V DC
Collection time	10ms/div
Trigger mode	Auto
All other settings	Default values

- Adjust the 'pot' and notice the effect on the oscilloscope trace.
- Select two widely different settings for the variable resistor, and save the resulting Picoscope traces for your records.
- For each signal, measure the (average) amplitude and period of the oscillation.
- Record your results in the Student Handbook and answer the questions raised there.

(The next worksheet uses a modified version of this circuit. You may wish to keep it to speed up assembly of the next system.)



WORKSHEETS

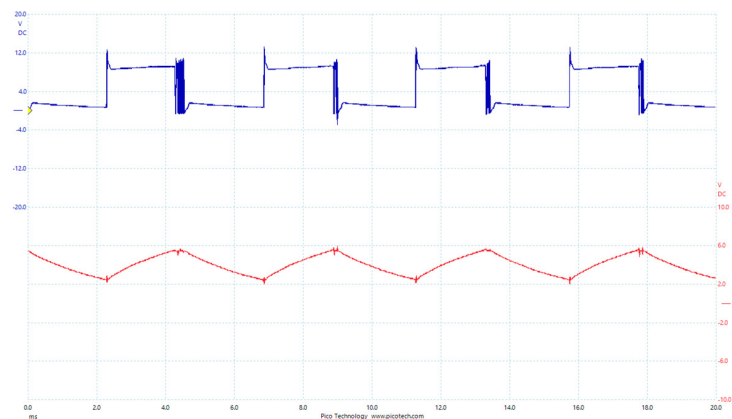
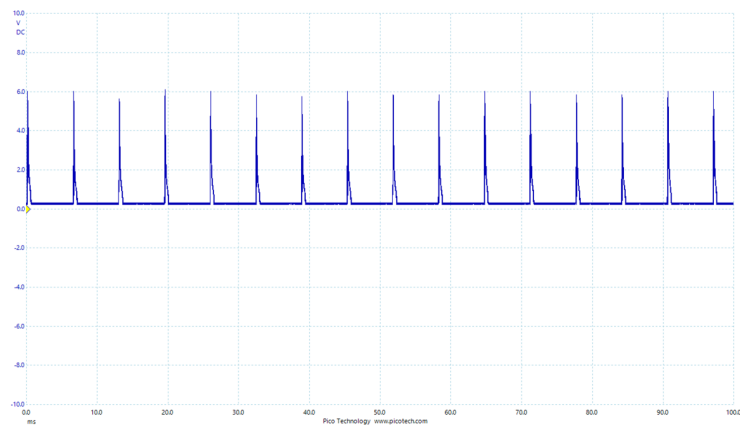
Worksheet 14 - The UJT Relaxation Oscillator

So What?

The mechanism:

- Initially, the UJT has a relatively high resistance.
- The capacitor starts charging.
- When the voltage across the capacitor is sufficient, it forward biases the p-n junction and a large current flows into the UJT, to base 1.
- This floods it with free charge carriers, reducing its resistance drastically.
- The capacitor is almost short-circuited and discharges quickly.
- The p-n junction switches off and the process repeats.

The following traces were obtained from this circuit. They show the signal across the 180Ω resistor for two settings of the variable resistor, giving a fast and a slow oscillation.



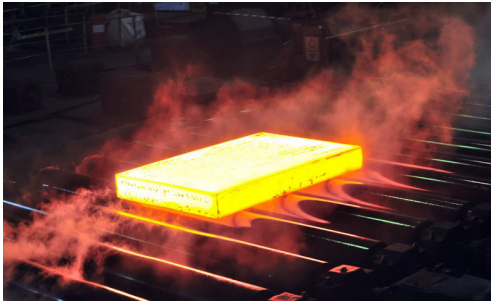
Challenge:

- Use Picoscope, with the same settings, to examine (separately) the following :
- The signal across the 470nF capacitor;
- The signal at base 2 of the UJT.
- Using Picoscope with faster collection time (timebase) settings, capture one 'spike'.

Can you identify the capacitor discharge curve?

WORKSHEETS

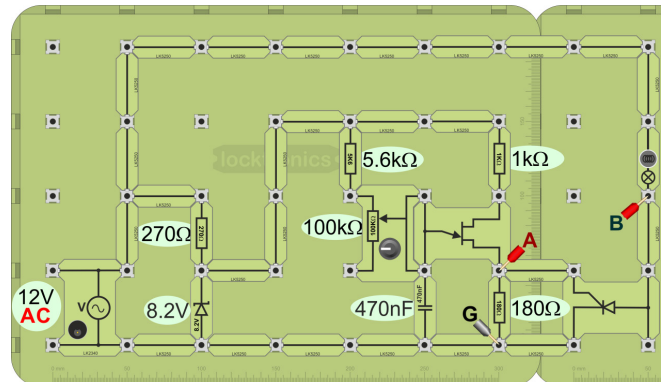
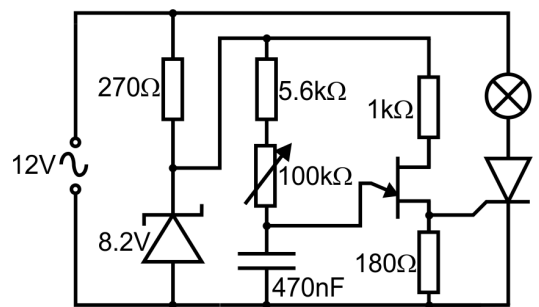
Worksheet 15 - Lamp Control - UJT and Thyristor



The thyristor is designed to switch huge currents and voltages, hundreds of amps, thousands of volts, in devices like the motors that roll steel in steel mills. To do so, they must switch on and off extremely rapidly. To linger in between these states would dissipate so much energy in the thyristor that it would be destroyed. 'Instant' switching requires trigger pulses that rise extremely rapidly. The 'spikes' generated by the UJT relaxation oscillator are ideally suited.

Over to you:

- Build the circuit shown opposite, which uses a 12V **AC** power supply. It is a modification of the previous circuit, extended by adding:
- A zener voltage regulator to provide a DC supply for the UJT;
- A thyristor, triggered by the UJT pulses, to control the brightness of a lamp.
- Set up a Picoscope to monitor:
- The output of the UJT, (across **A** and **G**);
- The thyristor output (across **B** and **G**).



Suitable Picoscope settings:

Input range: A	+/-20V DC
Collection time	10ms/div
Trigger mode	Auto
All other settings	Default values

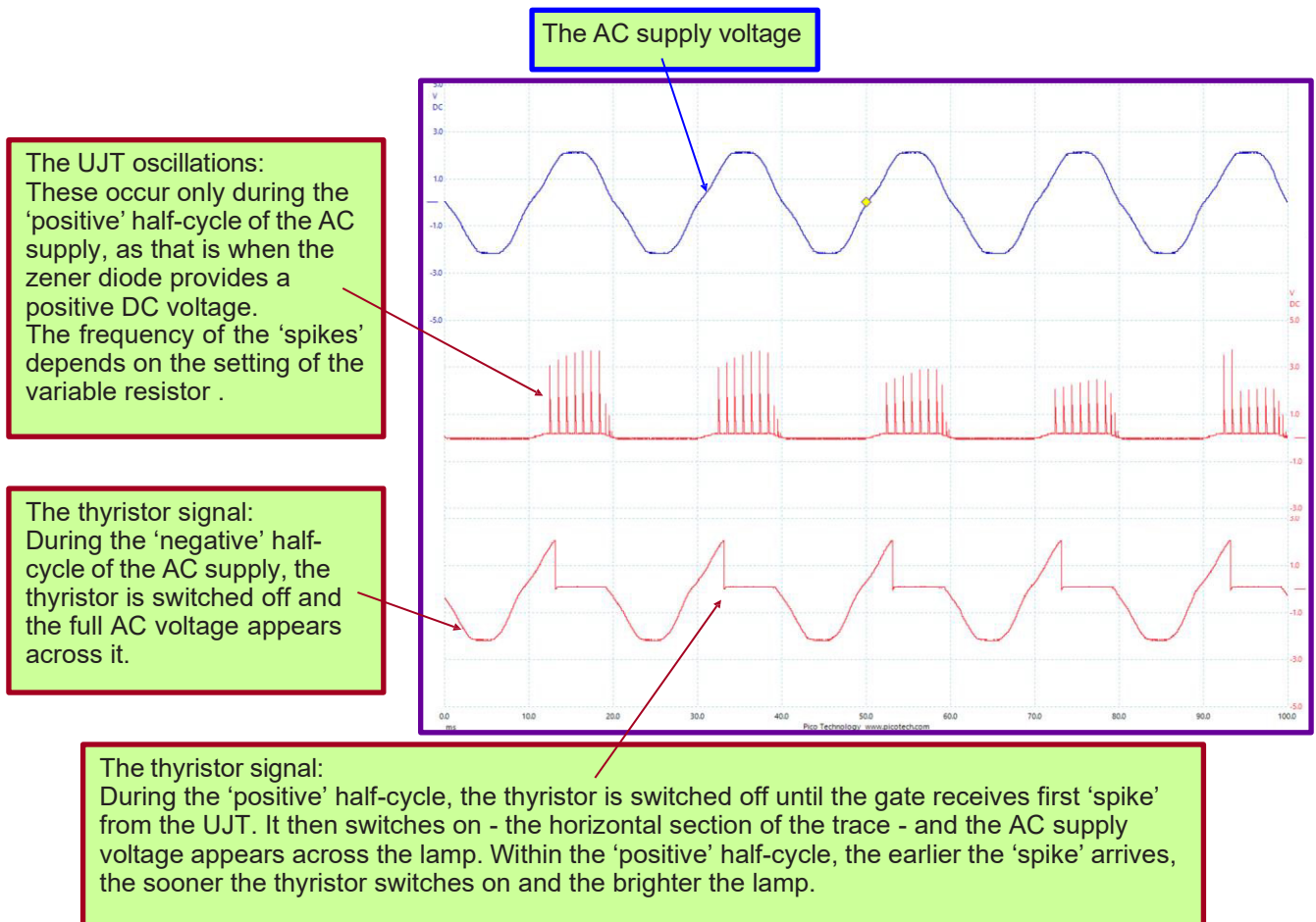
- Adjust the 'pot'.
- Notice the effect on the brightness of the lamp.
- Select two settings for the variable resistor, one giving a bright light and the other dim, and save or print the resulting Picoscope traces for your records.
- Answer the questions raised in the Student Handbook.

WORKSHEETS

Worksheet 15 - Lamp Control - UJT and Thyristor

So What?

The following diagram is a composite of traces taken from the circuit.



Circuit design considerations:

The 180Ω resistor:

- Even before the UJT fires, a small current of a few milliamps flows through this resistor, via the 1kΩ resistor and the UJT itself. (Assuming ~6kΩ for the inter-base resistance of the UJT, this current will be $\sim 8.2 / 7k$ i.e. $\sim 2mA$.) The resistor value is chosen so that the voltage generated by this current is not big enough to trigger the thyristor into conduction.
- A low value of resistance means that there is less chance of spurious noise spikes triggering the thyristor inadvertently.

WORKSHEETS

Worksheet 16 - Voltage Conversion - Half-Wave Rectification



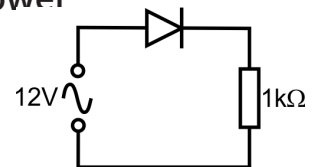
For a number of reasons, electricity is usually generated as AC. However, most electronic circuits require DC.

Rectification is the process of turning AC into DC. The diode is the device used to make this conversion. There are several ways in which it can be used to do this.

This worksheet looks at the simplest - the half-wave rectifier.

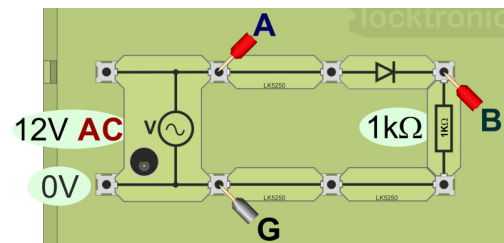
Over to you:

- Build the circuit shown opposite. The $1\text{k}\Omega$ resistor represents the electronic circuit. **Notice that we are using the 12V AC power supply!**
- Set up a Picoscope to monitor:
- The voltage across the AC supply, (connections A and G)
- The voltage across the $1\text{k}\Omega$ resistor, (connections B and G);



Suitable Picoscope settings:

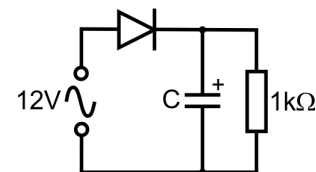
Input range: A	+/-20V DC
Collection time	10ms/div
Trigger mode	Auto
All other settings	Default values



- Save the traces for your records, or print them out .

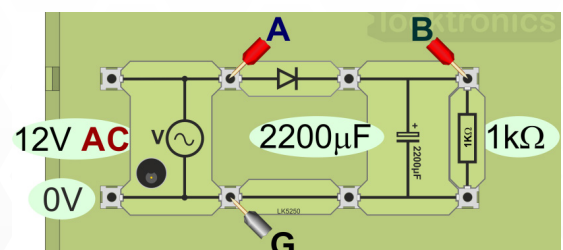
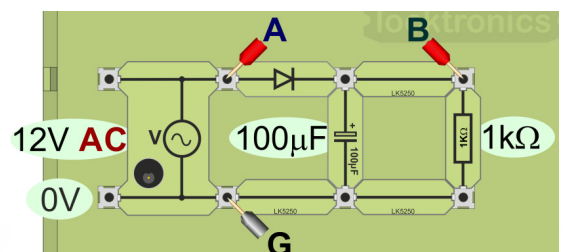
The performance is improved by adding a capacitor, known as a 'smoothing' or 'reservoir' capacitor. Its effectiveness depends on its size and on the current drawn from the rectifier.

- Modify the circuit by adding capacitor 'C' as shown in the second diagram. To begin with, use a $100\mu\text{F}$ capacitor.



Take care to connect the capacitor the right way round, as shown in the diagram!

- With the same Picoscope settings as before, record the signal across the AC supply and $1\text{k}\Omega$ load and save it for your records.
- Now swap the capacitor for a bigger value, $2200\mu\text{F}$, as shown in the bottom diagram.
- Record the new signals across the AC supply and $1\text{k}\Omega$ load and save it for your records.
- Answer the questions in the Student Handbook.



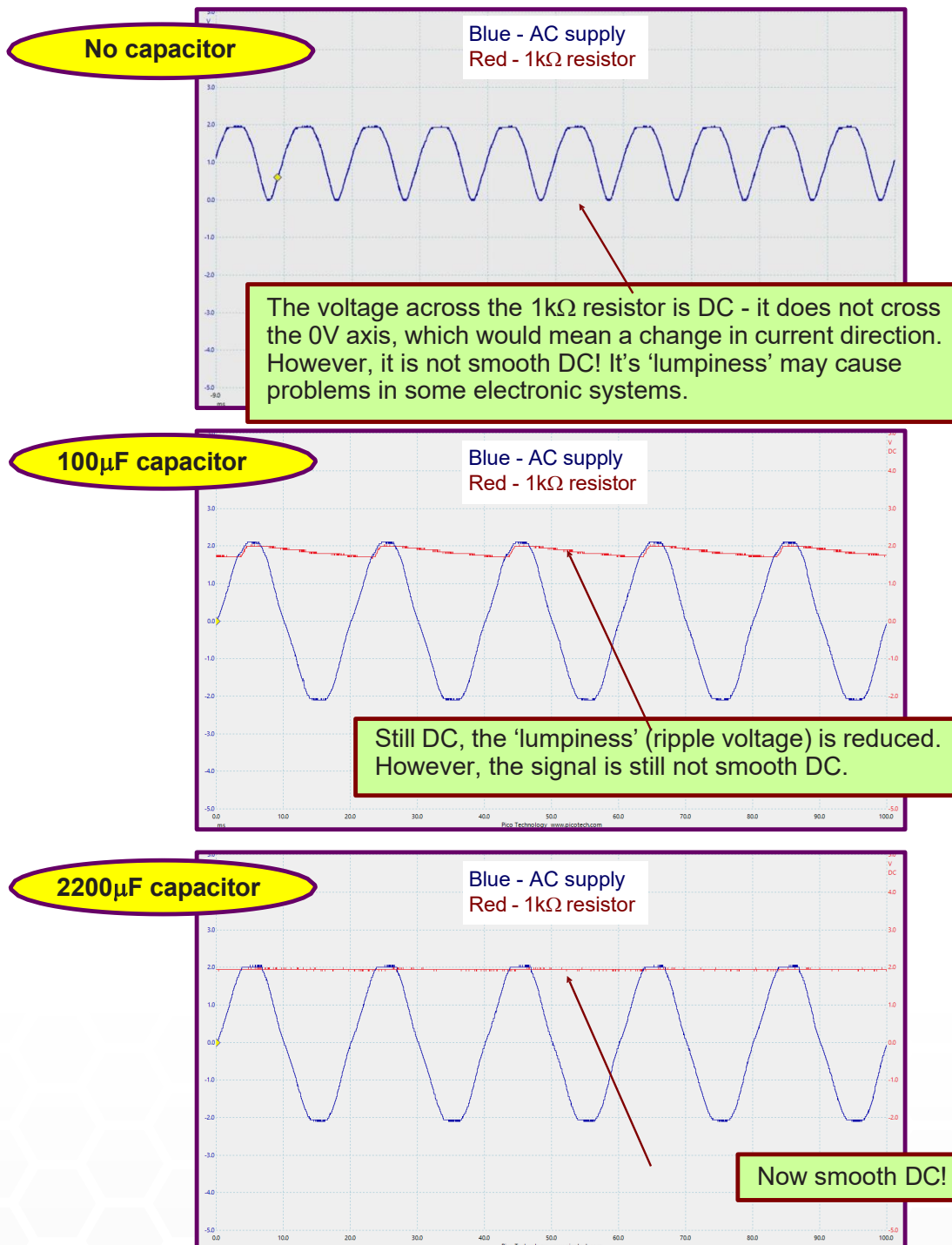
WORKSHEETS

Worksheet 16 - Voltage Conversion - Half-Wave Rectification

So What?

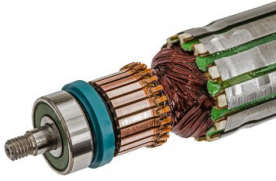
The following are typical traces from this investigation. The signal amplitude appears to be around 2.0V because the 'X10' switches on the probes were used, for clarity.

The actual amplitude was slightly greater than 20V.



WORKSHEETS

Worksheet 17 - Controlled Half-Wave Rectification



Controlled rectification combines AC to DC conversion with the ability to vary the output voltage and so the speed of a motor, brightness of a lamp, etc.

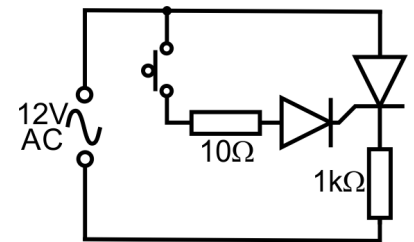
This worksheet looks at controlled half-wave rectification.

Over to you:

- Build the circuit shown opposite.

The $1\text{k}\Omega$ resistor represents the electronic circuit.
The diode and 10Ω resistor protect the thyristor.

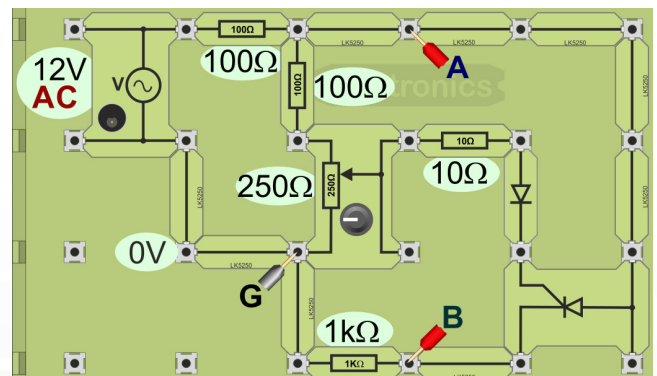
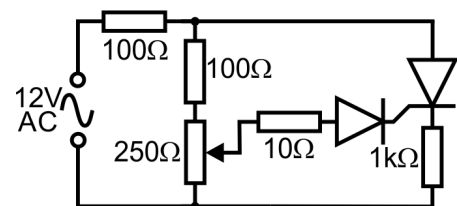
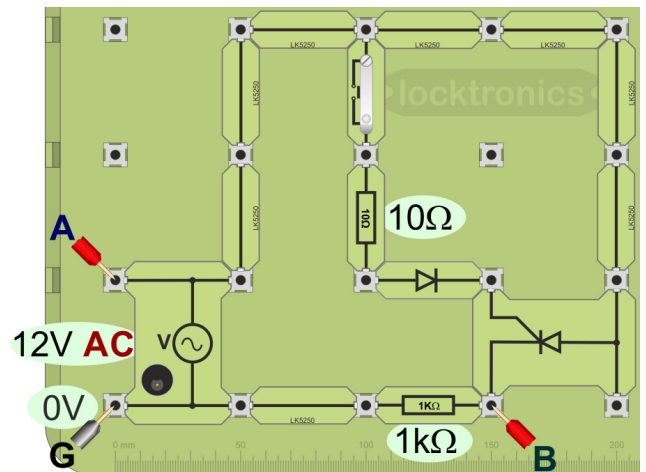
- Set up a Picoscope to monitor:
- The voltage across the AC supply, (connections **A** and **G**)
- The voltage across the $1\text{k}\Omega$ resistor, (connections **B** and **G**).



Suitable Picoscope settings:

Input range: A	+/-20V DC
Collection time	10ms/div
Trigger mode	Auto
All other settings	Default values

- Notice the effect of pressing the switch. Under forward bias, current flows into the gate terminal. The resulting current through the load is DC, (but not smooth).
- Save or print the results for your records.
- Next, modify the trigger circuit by adding two 100Ω resistors and 250Ω 'pot', as shown opposite. (The resistors reduce power dissipation in the 'pot' and other components. The 250Ω 'pot' allows the gate voltage to be varied.)
- Notice the effect of adjusting the 'pot'.
- Use Picoscope, with the same settings, to record the signals across the modified supply (at **A**,) and across the $1\text{k}\Omega$ load (at **B**,) for two different settings of the 'pot'.
- Save or print them for your records.
- Answer the questions in the Student Handbook.

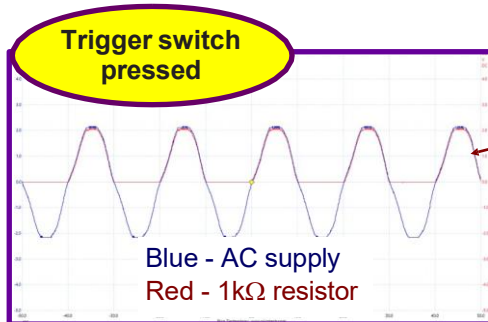


WORKSHEETS

Worksheet 17 - Controlled Half-Wave Rectification

So What?

In the following traces, the 'X10' switches on the probes were used, for clarity.



As before, the voltage across the 1kΩ resistor is DC. It does not cross the 0V axis. As soon as the thyristor is forward biased, it begins to conduct and continues to do so until the supply voltage reverses.

The next four traces relate to the second circuit. The 'pot' outputs a proportion of the modified supply voltage. When this reaches ~0.7V, the thyristor starts to conduct. The value of supply voltage at which this occurs depends on the slider position.



The thyristor conducts almost immediately each half-cycle. The effect is the same as in simple half-wave rectification.



Conduction is delayed each half-cycle. The average output voltage is reduced.

Challenge:

- Add a 2200μF smoothing capacitor across the output **connected the right way round!**
- Connect a motor (and flywheel diode) across the output.
- Use the Picoscope to verify that the output is smooth DC and that the motor speed can be varied.
- Answer the questions in the Student Handbook.



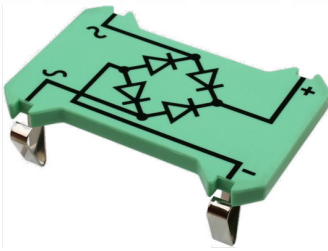
This shows the result of smoothing this waveform - a 6V output.



The result of smoothing is again DC, but lower in voltage, around 0.5V.

WORKSHEETS

Worksheet 18 - Voltage Conversion - Full-Wave Rectification



A half-wave rectifier circuit uses only one diode, but it does not make efficient use of the electrical energy on offer. For half of the time, no current at all flows through the load.

A full-wave rectifier overcomes this limitation, but uses a number of diodes to do so, and so drops more of the AC voltage across them.

Over to you:

- Build the circuit shown opposite. Again, the 1kΩ resistor represents the electronic circuit. **We are still using the 12V AC power supply!**
- Set up a Picoscope to monitor the voltage across the AC supply, (connections **A** and **X**).

Suitable Picoscope settings:

Input range: A	+/-20V DC
Collection time	10ms/div
Trigger mode	Auto
All other settings	Default values

- Save the resulting files, or print them out.
- Now move the probes to monitor the voltage across the 1kΩ resistor, (connections **B** and **Y**).
- Again, save the results file, or print it out .

Important!
If the oscilloscope has two input channels, **DO NOT** attempt to monitor both signals at the same time!

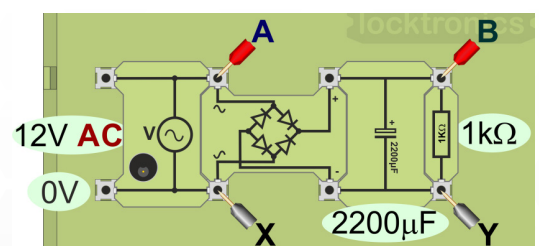
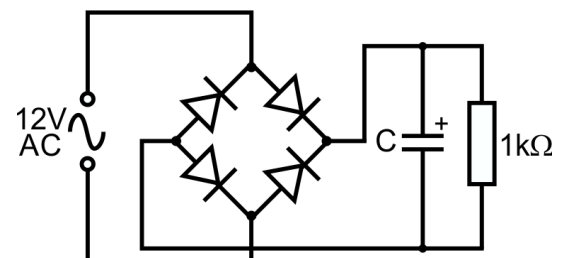
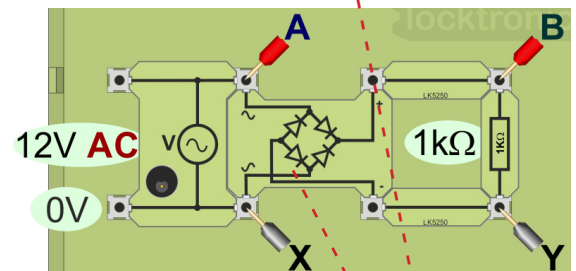
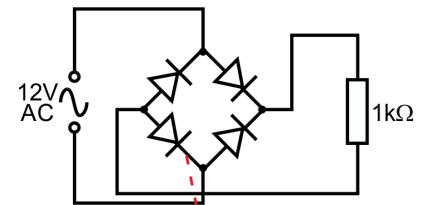
This will short-circuit a diode. (This one!)

The DC output is steadier than that for half-wave rectification, but still varies. The remedy is the same as in the last investigation - a large capacitor connected across the rectifier output.

- Modify the circuit by adding the capacitor as shown in the second diagram.

Once again, take care to connect the capacitor the right way round, as shown in the diagram!

- To begin with, use a 100μF capacitor. Then swap it for a 2200μF capacitor, (shown in the layout).
- For both, record the signals across the AC voltage and 1kΩ load and save or print them out.



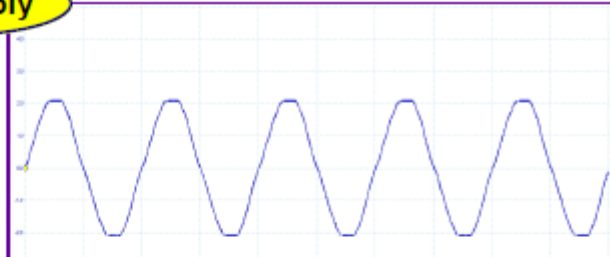
WORKSHEETS

Worksheet 18 - Voltage Conversion - Full-Wave Rectification

So What?

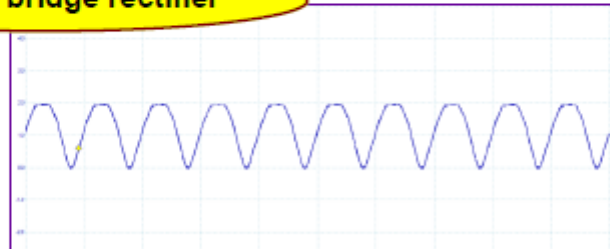
The following traces were obtained from the investigation.

AC supply



Once again, the 'X10' switches on the probes were used because the actual amplitude of the AC supply was slightly greater than 20V.

Output of bridge rectifier



The voltage is DC throughout - it does not cross the 0V axis. However, it is not smooth DC!

100 μ F smoothing capacitor



Still not smooth DC, but better than the ripple voltage for the half-wave rectifier. The ripple voltage amplitude is smaller and the frequency is twice as big.

2200 μ F smoothing capacitor



Now smooth DC!

WORKSHEETS

Worksheet 19 - Zener Diode Voltage Regulator



An essential part of any electronic system, the power supply has the task of converting the AC mains electricity into DC and then delivering a steady voltage no matter what.

Part of its construction includes a voltage regulator, which aims to maintain a steady output voltage over a range of output currents.

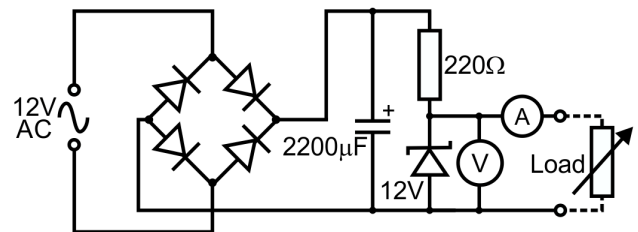
The zener diode is at the heart of most voltage regulators because of its ability to deliver a range of currents with little change in the voltage across it.

Over to you:

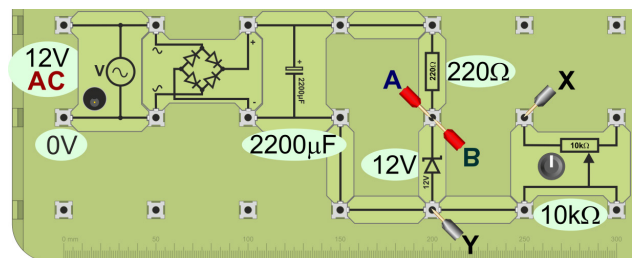
In the circuit that follows, the full-wave rectifier converts the AC supply to DC. It is followed by a zener diode voltage regulator, the focus of the investigation, which supplies current to a variable resistor, representing the load connected to the power supply. Adjusting it changes the output current delivered. The large capacitor smoothes the output.

- Build the circuit shown, which uses the 12V AC power supply.

Once again, take care to connect the capacitor the right way round!



- Connect a voltmeter, set to read DC voltages up to 20V, to points A and Y, to monitor the output voltage.
- Switch on and measure the output voltage, V_{OUT} , with no output current ($I_{LOAD} = 0mA$).
- Connect an ammeter, set to read DC currents up to 200mA to points B and X, to monitor the output current, I_{LOAD} .
- Adjust the 'pot' to give an output current, I_{LOAD} , of 5mA and read the output voltage, V_{OUT} .
- Record it in the table in the Student Handbook.
- Adjust the 'pot' to give output currents of 10mA, 15mA, 20mA, 25mA, 30mA and 35mA in turn. For each, measure and record the output voltage.
- Use your results to plot a graph of V_{OUT} against I_{LOAD} and use it to answer the question in the Student Handbook.



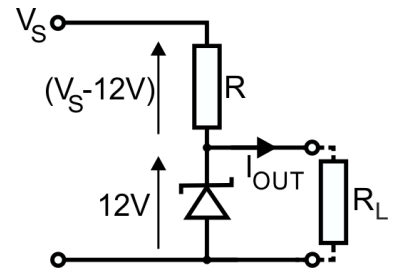
WORKSHEETS

Worksheet 19 - Zener Diode Voltage Regulator

So What?

The analysis goes like this:

- The supply has a peak voltage of $12 \times \sqrt{2} = 17.0\text{V}$.
- Assuming a voltage drop of $2 \times 0.7 = 1.4\text{V}$ across the bridge rectifier, gives a DC voltage to the voltage regulator of $V_S = 15.6\text{V}$.
- Voltage across zener diode = 12V , leaving $15.6 - 12 = 3.6\text{V}$ across resistor R.



Power rating of zener diode = 500mW maximum, (from Locktronics Technical Guide).

Using ' $I = P/V$ ', **maximum** current through zener diode = $500/12 = 41.7\text{mA}$.

This is the **maximum** permissible current through resistor R.

Hence, using ' $R = V/I$ ', **minimum** value of resistor $R = 3.6/41.7\text{mA} = 86.3\Omega$. The investigation used a value of 220Ω .

When 3.6V is dropped across it, current through it = $3.6/220 = 16\text{mA}$. This dissipates $16 \times 12 = 196\text{mW}$ when it flows through the zener diode - less than the maximum power rating!

To keep the zener diode in reverse breakdown, it needs to pass a current of at least 5mA .

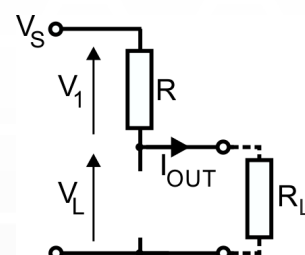
Hence, the maximum permissible output current, $I_{\text{OUT}} = 16 - 5 = 11\text{mA}$.

If a greater current is drawn from the output, then the zener diode comes out of reverse breakdown and behaves like a 'normal' reverse-biased diode and stops conducting.

The circuit then behaves like the one shown opposite - a straightforward voltage divider:

The voltage V_L across the load is given by:

$$V_L = \frac{V_S \times R_L}{R + R_L}$$



WORKSHEETS

Worksheet 20 - The 7805 Voltage Regulator



Many electronic devices are now solar-powered. There are obvious advantages to this and an obvious disadvantage - the sun does not shine all the time - at night, inside buildings, during bad weather... .

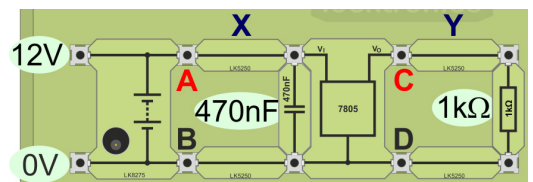
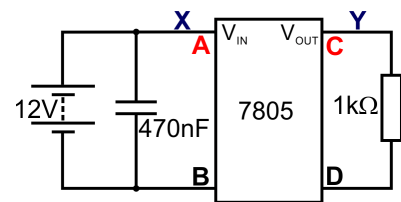
To overcome this, they contain batteries which are charged from the photovoltaic panel. To protect the battery, they often contain voltage regulators like the 7805, studied here.

Over to you:

In the following circuits, the $1\text{k}\Omega$ resistor represents the circuit supplied by the regulator. The 470nF capacitor filters out high frequency noise in the power supply, to make it more stable. This is especially important when a switched-mode power supply is used.

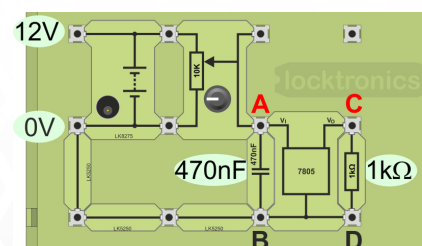
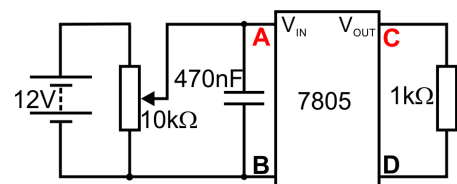
1. Power issues:

- Build the circuit shown opposite.
- Connect a voltmeter, reading DC voltages up to 20V, to points **A** and **B**, to measure the regulator input voltage, V_{IN} .
- Then connect it to points **C** and **D** to measure the output voltage, V_{OUT} .
- Remove connecting link **X** and replace it with an ammeter, reading DC currents up to 20mA, to measure the input current, I_{IN} .
- Replace **X**. Next, remove **Y** and in the same way measure the output current, I_{OUT} .
- Record all readings in the Student Handbook and use them to calculate the efficiency of the voltage regulator.



2. Line regulation:

- Modify the circuit by adding a 'pot' to allow the input (line) voltage to change.
- Use the 'pot' to adjust the input voltage to each of the values given in the table in the Student Handbook.
- Each time, measure the resulting output voltage and complete the table with your measurements.
- Answer the question given in the Student Handbook.



WORKSHEETS

Worksheet 20 - The 7805 Voltage Regulator

So What?

Voltage regulators are a form of DC-to-DC converter - the output DC voltage and current are different from the input DC voltage and current.

The language of voltage regulation:

Ideally, regulation comes in two forms:

Line regulation - the **output voltage** is immune to changes in the **input (line) voltage**.

Load regulation - the **output voltage** is immune to changes in the **output current**.

There are two categories of voltage regulator - **linear** and **switching**.

Linear regulators sense changes in output voltage. A feedback loop adjusts the output current to try to return the output voltage to its preset value.

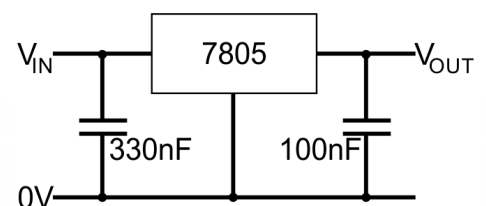
Switching regulators use the ability of capacitors and inductors to store electrical energy.

By switching the electricity supply to these devices on and off rapidly, the voltage across them is controlled over a range of output currents.

The following table compares their properties:

	Linear	Switching
Action	Step-down (buck) only Input voltage > output voltage	May be step-up (boost) or step- down (buck)
Efficiency	Low - depends on ($V_{IN} - V_{OUT}$)	High
Component count	Low Regulator plus two capacitors	High - Regulator plus capacitors, inductors and diodes
Size	Small (unless heat-sink needed)	Large
Noise	Low	High High frequency noise due to rapid switching
Cost	Low	High

The circuit diagram on the previous page includes a capacitor to reduce noise on the power supply lines. In practice, it is also advisable to use a second capacitor to filter noise on the output of the regulator, as the circuit diagram opposite shows. The values shown are the minimum to ensure stability.

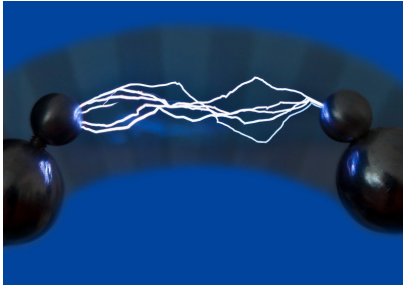


Challenge:

Monitor the load regulation by setting up the first circuit shown on the previous page and using different values of load resistor to change the output current. For each, measure the output voltage and current. Use your results to plot a graph, showing the variation of output voltage with output current.

Worksheet 21 - The Level Shifter

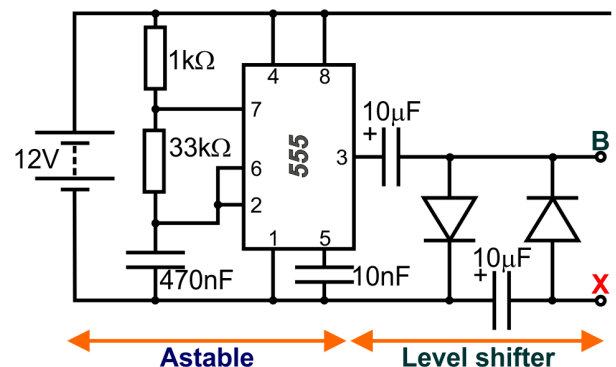
In 1932, physicists Cockroft and Walton used a 'voltage multiplier, based on a series of level shifter circuits to generate enormous DC voltages from a low voltage AC supply to power their subatomic particle accelerator.



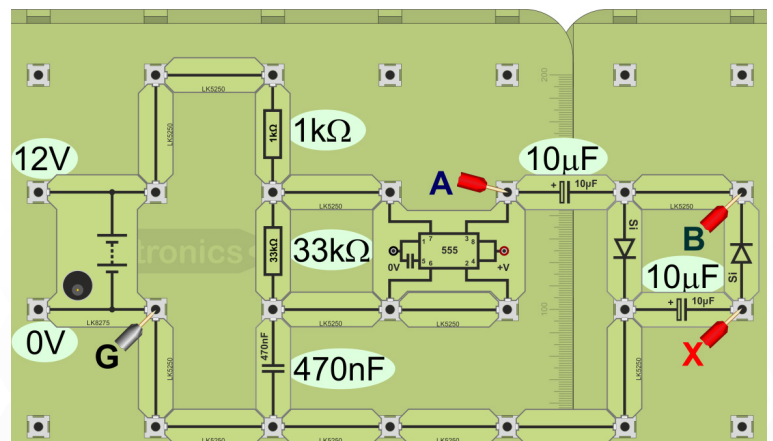
Applications include lasers, LCDs, x-ray machines, air ionisers and photocopiers.

The level shifter circuit consists of two sections:

- Build the circuit shown opposite. For clarity, the power leads to the 555 carrier have been omitted in the layout.
- Set up a Picoscope to monitor :
- The output of the astable, (**A and G**);
- Output B of the level shifter, (**B and G**).



- Then use it to monitor:
- The astable output, (**A and G**);
- Output **X** of the level shifter, (**X and G**).
- Save the resulting files, or print them out for your records.

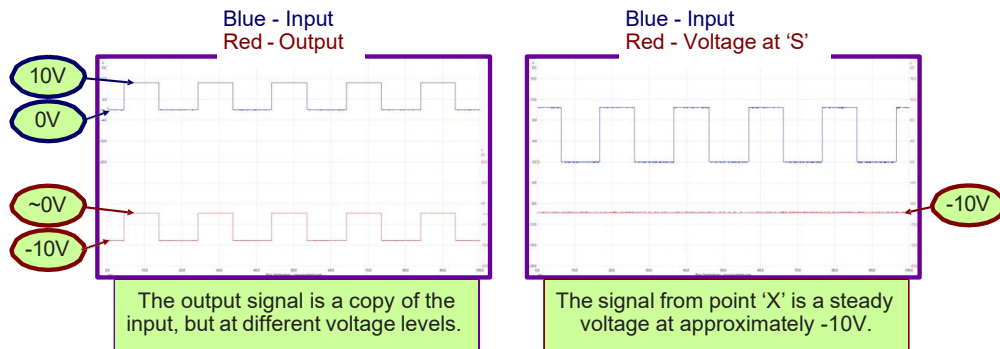


WORKSHEETS

Worksheet 21 - The Level Shifter

So What?

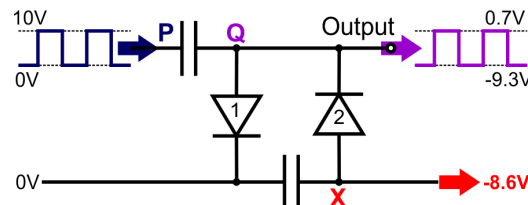
The following traces were obtained from the investigation. The Picoscope 'auto-arrange' function was used to separate them. The voltage measurements shown are approximate.



The analysis - (assuming ideal component characteristics):

Capacitors -

- Keep the same voltage **drop** across them until a current has had time to deposit or remove charge from the plates.
- A voltage **step** affects each plate equally. as there has been no time for a flow of charge to take place i.e. if one plate rises by 10V, then so does the other.



Point P -

- Follows the square wave signal i.e. 0V then 10V etc.

Point Q -

- As square wave voltage rises from 0 to 10V:
- The voltage step passes straight through the capacitor;
- The voltage at Q tries to rise to 10V, but diode 1, forward-biased, clamps it at +0.7V.
- As square wave voltage falls from 10 to 0V:
- The voltage step passes through the capacitor. The voltage at Q falls by 10V, to -9.3V.

The output signal is the signal at Q - a square wave oscillating between -9.3V and +0.7V.

Point X -

- When Q = -9.3V, diode 2 is forward-biased. X sits at 0.7V above Q, i.e. at -8.6V.
- When Q rises to +0.7V, diode 2 is reverse-biased. If no output current flows, the voltage at X is held at -8.6V.

WORKSHEETS

Worksheet 22 - The Buck Converter



A form of SMPS (switched-mode power supply,) a 'buck' converter is a DC-to-DC converter which steps down the voltage, so that its output is smaller than its input.

While this may sound simple - "Wouldn't a resistor do the same job?" - the clever part is to do it efficiently. A good design achieves an efficiency of more than 90%!

A typical application - to lower a laptop battery voltage from ~12V to ~1V for the processor chip.

Over to you:

The circuit diagram shows a simple buck converter driven by a 555 astable. The transistor buffers the astable, reducing the current taken from the 555 IC. The 120Ω resistor on the output represents the circuit load.

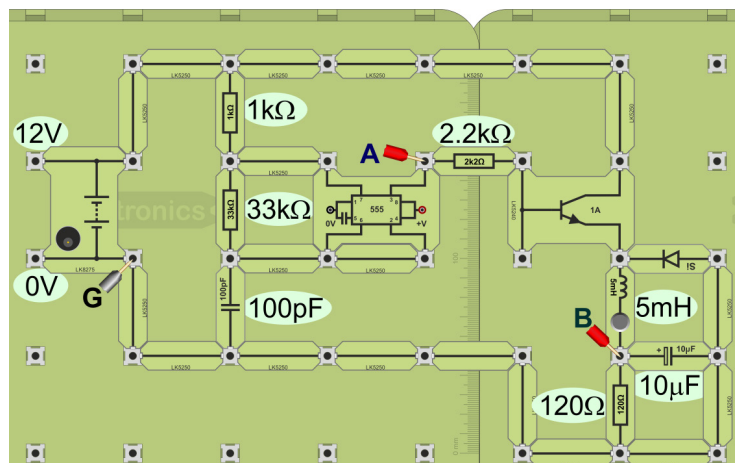
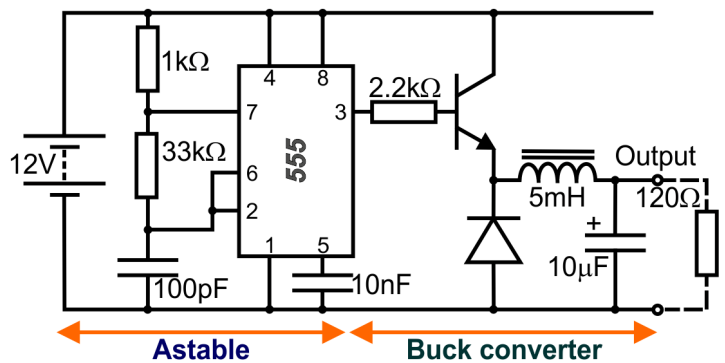
- Build the circuit shown opposite. Once again, for clarity, the power leads to the 555 carrier have been omitted from the layout.

Take care to connect the capacitor the right way round!

- Set up a Picoscope to monitor :
- The astable output, (A and G);
- The output of the buck converter, (B and G).

Suitable Picoscope settings:

Input range: A and B	Auto
Collection time	1μs/div
Trigger mode	Auto
All other settings	Default



- Save the resulting files, or print them out.
- Answer the question posed in the Student Handbook

WORKSHEETS

Worksheet 22 - The Buck Converter

So What?

These traces come from the simple buck converter circuit. They show a steady 4V output from the system.

The output is not well-regulated, as you can see by changing the load resistor, but it shows the principle of the buck converter.

The next trace was obtained by lowering the astable frequency by swapping the 100pF capacitor for a 100nF capacitor.

The output is clearly that of a charging and discharging capacitor, changing from around 2.5V to 5.5V.

The traces also show the output 'ringing' in response to the sudden steps in voltage caused by the square wave, the result of stray capacitance and inductance in the circuit.

The analysis: (well - one way to look at it!)

Its all down to the behaviour of **inductors and capacitors**.

Inductors hinder rapidly changing voltages (like AC).

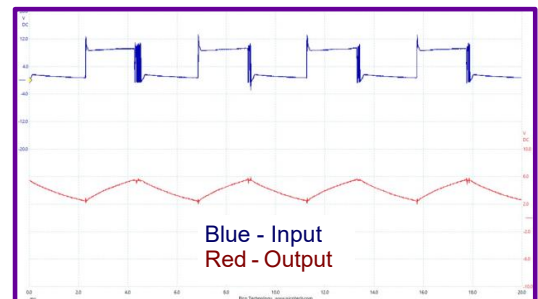
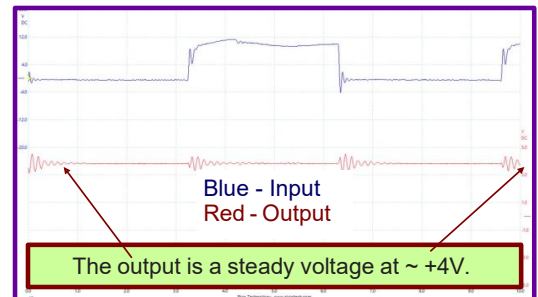
The higher the frequency, greater the hindrance. They generate a magnetic field inside the coil. A quandary - no current, no magnetic field - no magnetic field, no current!

In reality, current and magnetic field build slowly, storing energy in the magnetic field. When the external current stops, the magnetic field collapses, generating a current in the same direction.

Capacitors block DC currents, but offer little hindrance to high frequency AC.

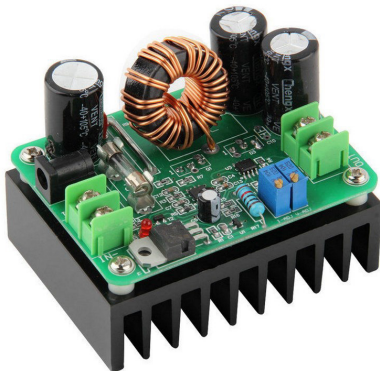
The quandary - they generate an electric field across the plates as the voltage rises - generate a voltage across the plates as the electric field rises.

In reality, both build together, storing energy in the electric field. When the external voltage stops, the capacitor acts as a 'battery' to replace it, using energy stored in the electric field.



WORKSHEETS

Worksheet 23 - The Boost Converter



A 'boost' converter steps **up** the **voltage**, so that the DC output voltage is bigger than the DC input voltage. (It is another form of switched-mode power supply.)

The conservation of energy law insists that current steps **down** - the output current is smaller than the input current.

One use is to step up the battery voltage in an electric car, to avoid the need for a large number of batteries. In a similar way they are used to power backup lightingsystems from a single battery.

Over to you:

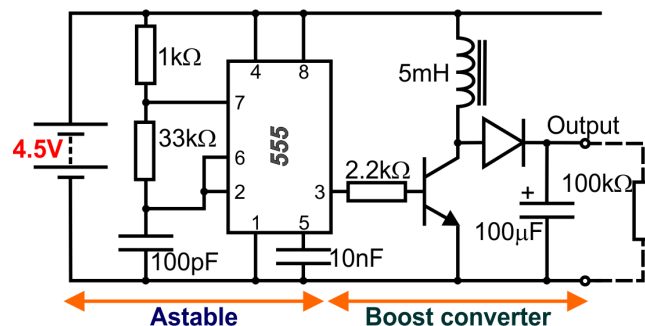
The circuit diagram shows a simple boost converter, again driven from a 555 astable. The two sections, the astable and the boost converter, have been labelled.

Once again, the transistor acts as a current buffer for the 555 IC. The 100kΩ resistor on the output represents the circuit load.

- Build the circuit shown opposite. The DC power supply is set to **4.5V**.

Take care to connect the capacitor the right way round!

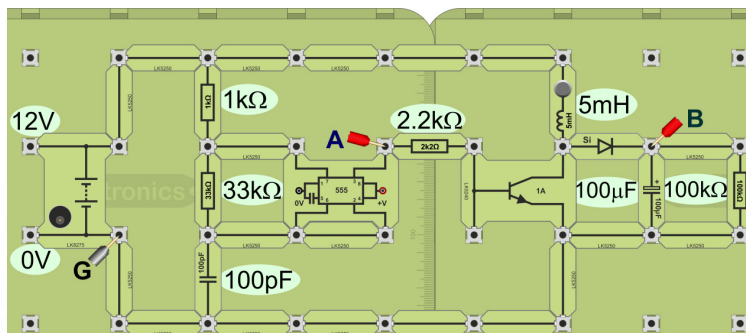
Again, for clarity, the power leads to the 555 carrier have been omitted.



- Set up a Picoscope to monitor :
- The astable output, (A and G);
- The output of the boost converter, (B and G).

Suitable Picoscope settings:

Input range: A	+/-5V DC
Input range: B	+/-20V DC
Collection time	2μs/div
Trigger mode	Auto
All other settings	Default



- Save the resulting files, or print them out, for your records.
- Answer the question posed in the Student Handbook.

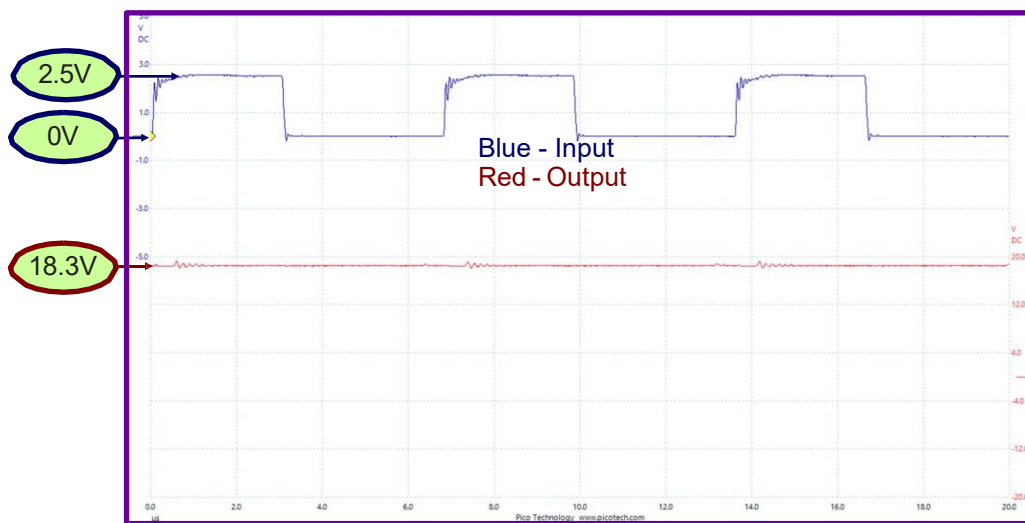
WORKSHEETS

Worksheet 23 - The Boost Converter

So What?

These traces were obtained from the boost converter circuit. The output is a steady 18.3V signal (apart from the unwanted ringing noise).

Once again, the output is not well-regulated, but the circuit illustrates the boost converter principle.



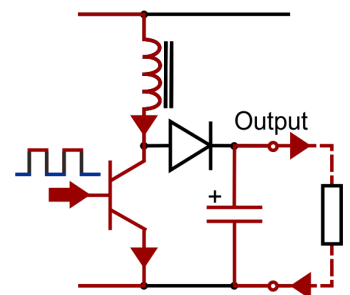
The analysis: (well - one way to look at it!)

Its still down to the behaviour of **inductors** and **capacitors**.

When the astable signal is **high**:

The transistor is on and very low resistance path to 0V opens.

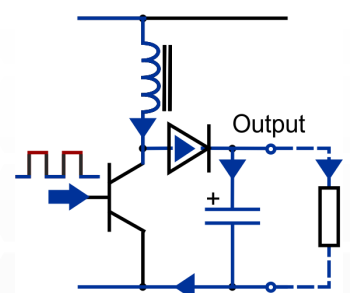
Current flows through the inductor, storing energy in the magnetic field. The diode is reverse biased. The electric field in the capacitor collapses as it 'funds' a current through the load.



When the astable signal is **low**:

The transistor turns off.

The diode is forward biased and energy stored in the inductor's magnetic field drives a current that both supplies the load and tops up the charge on the capacitor (storing energy in its electric field).



Worksheet 24 - The 555 Inverter

Now the opposite - DC to AC conversion, important in a number of areas:

- ## Over to you:

This inverter circuit consists of two sections:

-
- The diagram shows a 555 timer IC configured as an astable multivibrator. The supply voltage is 12V. The timing network consists of a 22kΩ resistor and a 100nF capacitor connected between pins 2 and 6, and a 100nF capacitor connected between pin 5 and ground. The output of the timer (pin 3) is connected to a three-stage RC filter. Each stage consists of a 1kΩ resistor in series with a 470nF capacitor to ground. The final output is taken from the last capacitor.

- Save the resulting files, or print them out.

- Investigate the effect of using different resistor and capacitor values for the astable. (The current values are chosen to match the response of the filter.)

WORKSHEETS

Worksheet 24 - The 555 Inverter

So What?

According to Fourier's theorem, a signal like a square wave can be created by combining a series of sine waves of different frequencies and amplitudes. (A sine wave is considered to be the simplest signal, as it contains only one frequency of oscillation.)

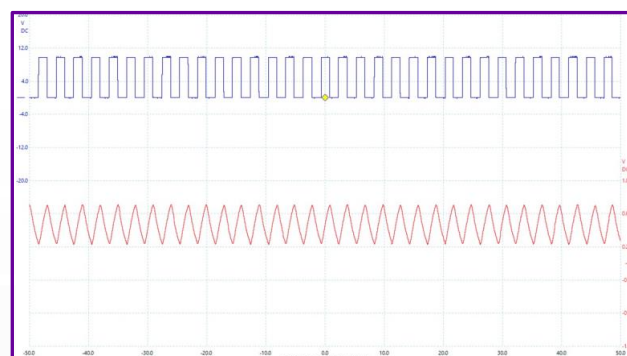
A spectrum analyser decomposes a signal to reveal these components. Its output is a graph showing frequency on the horizontal axis and amplitude on the vertical axis. Each 'spike' on the graph represents a single sine wave.

The following trace was obtained from the investigation. It shows the result of feeding the square wave from the astable into a spectrum analyser, identifying the series of sinusoidal components that go to make up the square wave signal. Their amplitude gets smaller and smaller as their frequency increases. The lowest frequency component, called the fundamental, represents the sine wave with the same frequency as the square wave.

If the low-pass filter removed all components with frequencies higher than the fundamental, the output would be a sine-wave signal with the frequency of the square wave.



The next diagram shows a voltage / time graph of the output of the filter subsystem when the square wave is inputted. The output is approximately a sine wave.



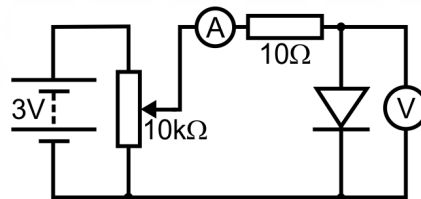


STUDENT HANDOUT



WORKSHEETS

Worksheet 1 - The p-n Junction Diode



The circuit shown above was used to investigate the forward-biased diode.

Results are given in the table:

Current through diode in mA	2	4	6	8	10	12	14	16	18	20
Voltage across diode										

When the diode is reverse-biased, _____

Compared to ideal diode characteristics, _____

Challenge - the LED:

Results for forward bias:

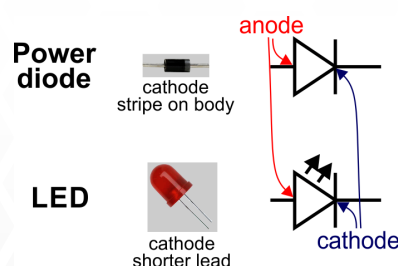
Current through diode in mA	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Voltage across diode										

When the LED is reverse-biased, _____

Summary:

A forward biased silicon diode has a voltage drop of ~0.7V across it.

A forward biased LED lights and has a voltage drop of ~2V across it.



WORKSHEETS

Worksheet 2 - The Zener Diode

All semiconducting diodes eventually break down when the reverse voltage is sufficiently high. In doing so, they are usually damaged, possibly destroyed.

The zener diode is designed to break down at a precise and much lower reverse voltage and in a controlled manner.

The behaviour of a typical zener diode is shown in the graph. The voltage labelled 'X' is known as the zener voltage, V_Z . At the zener voltage, a minimum current is required (usually a few mA,) to keep the diode in reverse breakdown.

Your results:

Forward bias - current starts to flow at V.

Reverse bias - current starts to flow at V.

Devices are available with a range of zener voltages, usually matching the values in the E24 resistor series. Another important parameter is the power rating, P_D , of the zener diode. This can be used to calculate the maximum permissible current, using the formula: $I_{max} = P_D / V_Z$.

For example, a 1N5913B zener diode has a zener voltage of 3.3V and a steady-state power rating of 1W. This means that it can sustain a reverse current of $1 / 3.3 = 303\text{mA}$.

Typical application - a reference voltage source:

As the graph shows, the voltage across a zener diode in reverse breakdown changes very little as the current changes. This makes it very useful as a constant voltage source in a number of applications, such as ADCs (analogue-to-digital converters) and DACs (digital-to-analogue converters).

Analysis:

Reference voltage = 12V (set by the zener voltage of the diode.)

Supply voltage, V_s , is shared between the zener diode and resistor, R.

Ignoring any current drawn from the voltage source output, the same current, I , flows through both.

Suppose that: $V_s = 15\text{V}$, $R = 300\Omega$

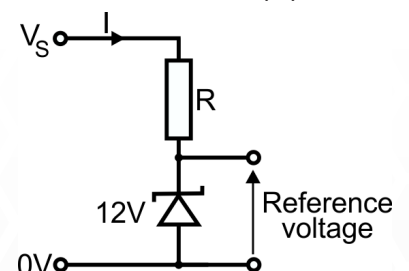
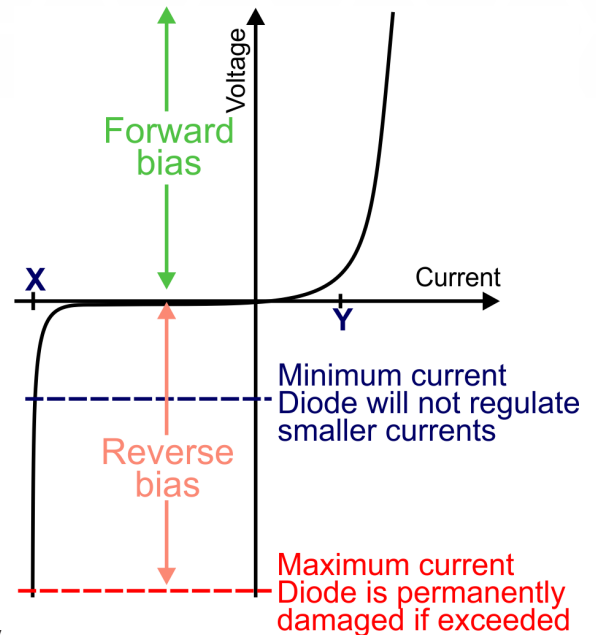
The voltage across resistor $R = V_s - V_Z = 15 - 12 = 3\text{V}$.

Applying Ohm's law to the resistor,

current $I = V / R = 3 / 300 = 0.01\text{A} = 10\text{mA}$.

Power dissipated in the zener diode = $V_Z \times I = 12 \times 10 = 120\text{mW}$.

Power dissipated in the resistor = $V \times I = 3 \times 10 = 30\text{mW}$.



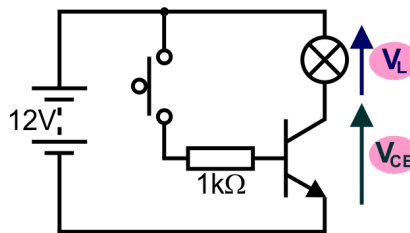
WORKSHEETS

Worksheet 3 - On/Off Control - BJT Switch

Behaviour of a switch:

Switch	V_s	V_L	Lamp (On/Off)
Open			
Closed			

Behaviour of a transistor switch:



Switch	V_s	V_L	Lamp (On/Off)
Open			
Closed			

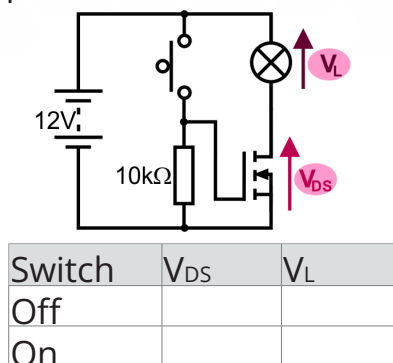
Explain why the transistor can be described as a switch in this arrangement.

Write an explanation that a fellow student would understand as to why a diode, connected in reverse parallel, is needed when the motor is switched on and off by a transistor.

WORKSHEETS

Worksheet 4 - On/Off Control - MOSFET Switch

Behaviour of a MOSFET switch



Explain why the MOSFET can be described as a switch in this arrangement.

Use the datasheet for the **RFP30N06LE** MOSFET to find the following information:

- Maximum continuous drain current;
- Maximum power dissipation (assuming the use of a heat-sink);
- Maximum value of $R_{DS(ON)}$, (drain to source 'on' resistance).

Use this information to work out the power dissipation in the MOSFET when it is passing maximum (continuous) drain current.

What happens to the voltmeter reading when your finger closes the gap between the posts of the Universal Component carrier?

WORKSHEETS

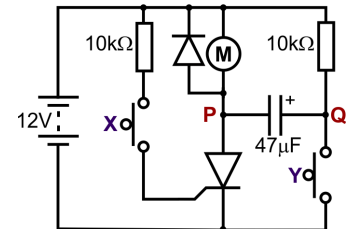
Worksheet 5 - On/Off Control - Thyristor Switch

Thyristors:

- Conduct only when forward biased – anode more positive than cathode;
- Are triggered into conduction by a sufficiently large pulse of current into the gate;
- Are self-latching - once turned on, they stay on, as long as a sufficiently large current flows from anode to cathode.

The circuit shows a typical DC thyristor switching circuit, using capacitor commutation.

The motor is initially switched off.



What happens when you press and release switch X?

Explain why this happens.

What happens when you press and release switch Y?

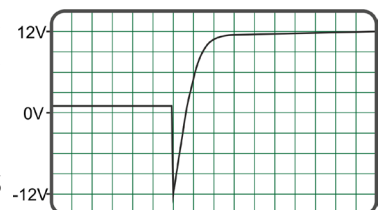
The diagram represents the oscilloscope trace, showing the voltage across the thyristor before and after switch Y is pressed and released.

Add labels to identify:

- The portion of the trace where the thyristor is switched on;
- The portion of the trace where the thyristor is switched off;
- The point at which switch Y is pressed.

Hence, explain why the thyristor switches off when switch Y is pressed.

Hence, explain why the thyristor switches off when switch Y is pressed.



How does the thyristor switch behaviour differ from that of the BJT and MOSFET switches?

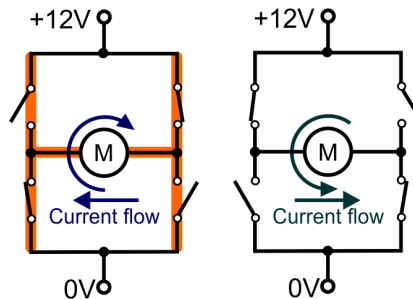
Give two advantages of the thyristor switch compared to the electromagnetic relay.

Explain the purpose of the flywheel diode in this circuit.

WORKSHEETS

Worksheet 6 - On/Off/Direction Control - H-Bridge

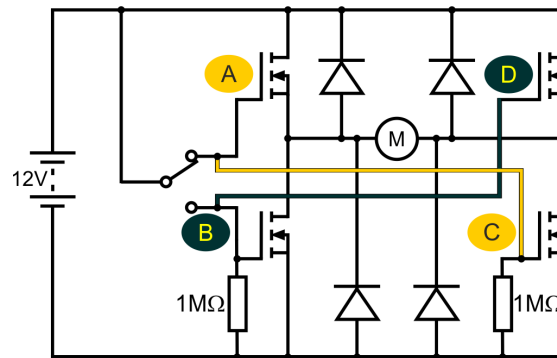
The principle is illustrated in the diagram below. The name 'H-bridge' comes from the 'H' con-figuration, highlighted in orange on the left-hand part of the diagram.



The direction of rotation of the motor can be controlled by operating the switches in the right order. The danger is that the power supply can be short-circuited if the switches are operated incorrectly. This can be avoided by using electronic switches, rather than mechanical ones.

The circuit diagram shows one way to do this, using MOSFETs as the switching devices. The changeover switch turns on either MOSFETs **A** and **C**, or MOSFETs **B** and **D**.

It cannot short-circuit the power supply!



Effect of the changeover switch:

Change switch position	Motor voltage	
	Left-hand side	Right-hand side
Off		
On		

How do these results show that the changeover switch controls both the on/off state of the motor and its direction of rotation?

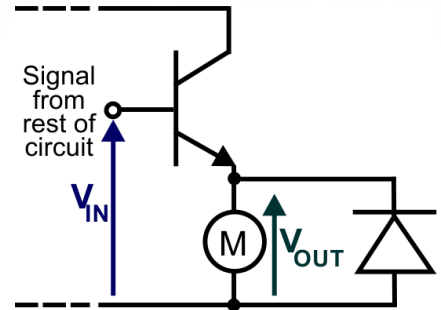
WORKSHEETS

Worksheet 7 - Motor Control - BJT Emitter Follower

The next step is graduated control where the load device is not simply on or off, but is supplied with a variable voltage, allowing different motor speeds, variable lamp brightness etc.

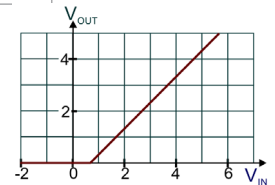
One way to do this uses a BJT connected as an emitter follower. The circuit diagram shows an emitter follower used to control the speed of a motor.

The relationship between input and output voltages is:



Input voltage V_{IN}	0	1.0	2.0	3.0	4.0	5.0	-1.0	-2.0	-3.0
Output voltage V_{OUT}									

Use your results to plot a graph of V_{OUT} against V_{IN} (i.e. the voltage transfer characteristics) for the emitter follower.



It should resemble the one shown opposite.

Interpreting the results:

- When the V_{IN} is greater than $\sim 0.7V$, the transistor starts to conduct.
- As a result, a voltage drop of $\sim 0.7V$ is created between base and emitter.
- The remainder of V_{IN} is dropped across the motor, as output voltage V_{OUT} .
- Hence, the **emitter follower relationship**:

$$V_{OUT} = V_{IN} - 0.7$$

Voltage gain: Voltage gain = V_{OUT} / V_{IN}
= ~ 1

Current gain: Output current through load = emitter current I_E
Input current = I_B
Current gain = output current / input

current

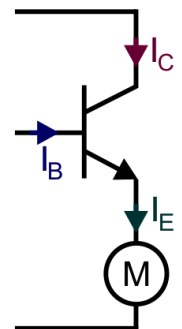
$$= I_E / I_B$$

From Kirchhoff's current law:
and

$$I_E = I_C + I_B$$

$$I_C \gg I_B$$

Hence current gain = $\sim I_C / I_B = \sim h_{FE}$ (the current gain of the transistor.)



Write an explanation for a fellow students to show that emitter follower has an overall power gain (= voltage gain x current gain).

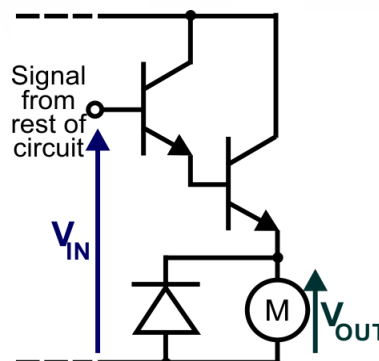
WORKSHEETS

Worksheet 8 - Motor Control - Darlington Driver:

Sometimes, one transistor just isn't enough!

One solution is to couple two transistors together in an arrangement known as a darlington pair, shown opposite driving a motor, once more.

The relationship between input and output is different. From the perspective of voltage, it is a double emitter follower. As far as current is concerned, it is a double current amplifier.



Your results:

Input voltage V_{IN}	0	1.0	2.0	3.0	4.0	5.0	6.0
Output voltage V_{OUT}							

With an input voltage of 5.0V:

input current I_{IN} = ... mA
output current I_{OUT} = ... mA

Power gain calculation:

Use your results to complete the following calculations:

Power gain = output power / input power,
where:

input power = $V_{IN} \times I_{IN}$
= $5 \times \dots\dots\dots$
= mW;

and output power = $V_{OUT} \times I_{OUT}$
= $\times$
= mW.

Hence, power gain = ...

Advantages of the Darlington pair follower:

- Very high current gain (= gain of T_1 x gain of T_2);
- Very high input impedance. (For a given output, the input current is tiny, as if the subsystem had a huge impedance.)

Disadvantages of the Darlington pair follower:

- Higher overall voltage drop between input and output (~1.4V compared to ~0.7V for the emitter follower);
- Higher saturation voltage, when switched on fully, resulting in higher power dissipation.

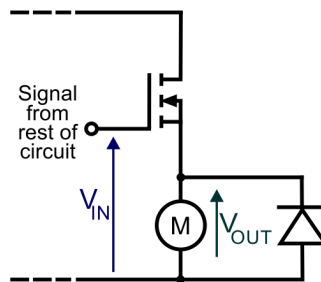
WORKSHEETS

Worksheet 9 - MOSFET Source Follower:

MOSFETs offer significant advantages over BJTs, including:

- Higher input impedance - less current required to operate it;
- Smaller power loss - the residual resistance, $R_{DS(ON)}$, of the MOSFET has less effect than the BJT forward voltage drop V_{CE} ($\sim 0.3V$) when the devices are switched on;
- Faster switching - conduction by majority, not minority carriers;
- No tendency for thermal runaway.

The circuit diagram shows a source follower used to control the speed of a motor.



Your results:

Input voltage V_{IN}	0	1.0	2.0	3.0	4.0	5.0	6.0
Output voltage V_{OUT}							

Compare the behaviour of the source follower and emitter follower subsystems. (You may need to do some research in textbooks and on the internet.)

With the input voltage at 6.0V, complete the table with your other measurements.

Use them to recalculate the voltage, current and power gain.

Voltage gain = ...

Current gain = ...

Hence **Power gain** = ...

Input voltage V_{IN}	6.0V
Output voltage V_{OUT}	
Input current, I_G	
Output current, I_D	

Does the power gain depend on the input voltage?

WORKSHEETS

Worksheet 10 - Motor Control - PWM:

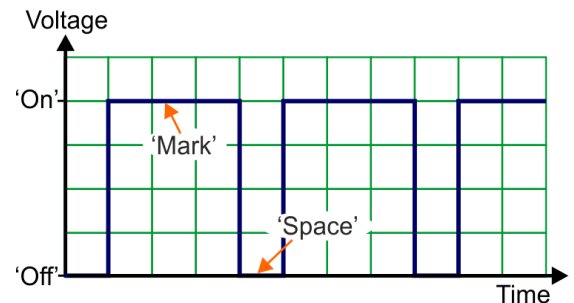
In pulse-width modulation, the output signal switches on and off rapidly and repeatedly.

The 'mark' is the time for which it is 'on'.

The 'space' is the time for which it is 'off'.

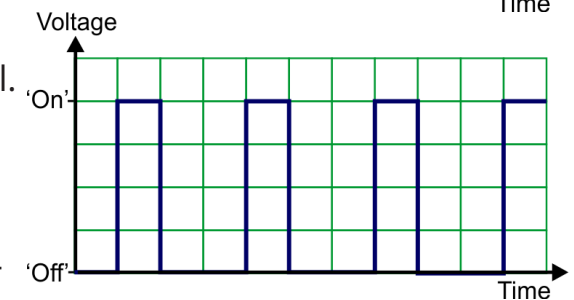
The signal shown has a mark-to-space ratio of 3:1.

The term 'duty cycle' is another measure of the same thing. It is defined as the percentage of time for which the output is 'on'. The signal shown has a duty cycle of 75%.



The second diagram shows a different PWM signal.

Calculate the mark-to-space ratio of this signal.



The speed of a motor is controlled by a PWM signal.

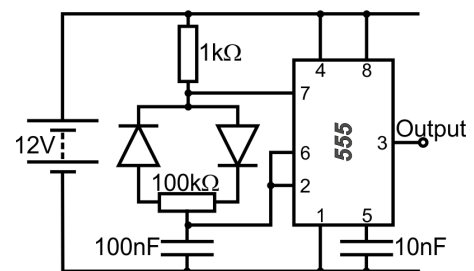
What happens to the speed when the mark-to-space ratio increases?

The circuit diagram shows a 555 timer used to generate a PWM signal.

Challenge:

With the 100nF capacitor:

- Time period of signal = ...
- Frequency of signal = ...



What is the effect on these readings of changing the capacitor value?

Write an explanation of why using PWM is more energy efficient than using a serial resistor to control the speed of a motor.

WORKSHEETS

Worksheet 11 - Phase Control

The voltage across the capacitor rises, as it charges up through the resistor.

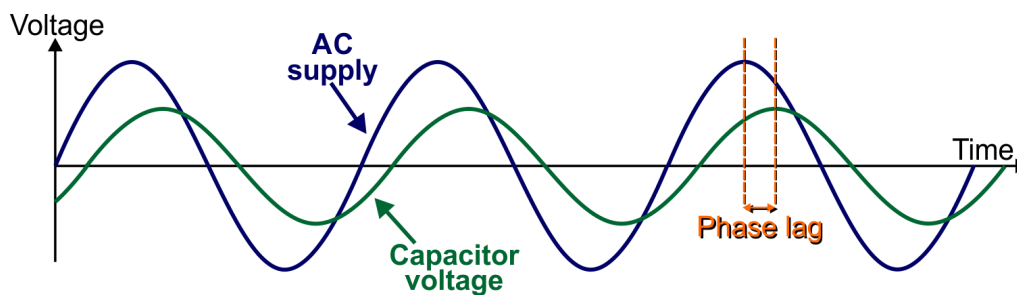
The bigger the capacitor, the longer it takes to charge up.

The bigger the resistor, the smaller the current and the longer it takes to charge the capacitor.

For these reasons, the voltage across the capacitor lags behind the supply voltage.

To add to the complexity, the supply voltage itself is changing - it is AC.

The result of all this is shown in the following graph:



Your results:

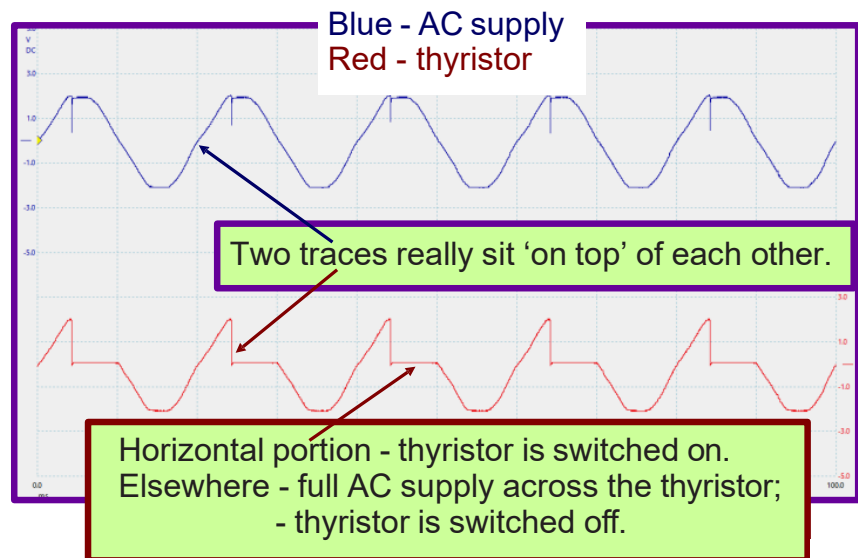
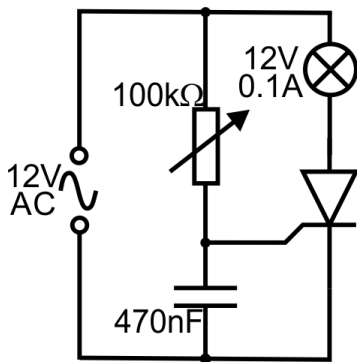
As the knob on the 'pot' is rotated clockwise, the resistance of the 'pot'
and so the phase lag

Increasing the capacitor value the phase lag.

WORKSHEETS

Worksheet 12 - Lamp Control - Thyristor

The circuit diagram for thyristor phase control and typical oscilloscope traces for the voltages across the thyristor and AC supply are shown below.



Interpretation:

AC 'positive' half-cycle:

- Thyristor triggered into conduction when gate (=capacitor) voltage rises sufficiently;
- Latches on for remainder of 'positive' half-cycle;
- Triggering does not happen immediately because of phase lag so conduction happens for less than the full 'positive' half-cycle. The lamp is dimmed.

AC 'negative' half-cycle - thyristor switches off.

The maximum phase difference between the capacitor signal and the AC supply is 90° with this arrangement. What effect will this phase difference have on the brightness of the lamp?

WORKSHEETS

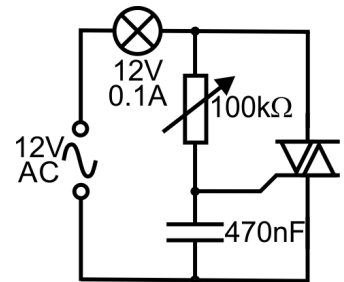
Worksheet 13 - Lamp Control - Triac

The thyristor is a rectifier. Current can flow through it in one direction only and so it is switched off for half of the time when powered by AC. The triac allows current flow in both directions and so delivers more power to the load.

The circuit diagram shows a triac under phase control.

Here, the load (the lamp) is positioned before the phase control system.

The oscilloscope traces show the voltages across the thyristor and AC supply when the lamp is at nearly full brightness:



'Spikes' show sudden current demand when the triac switches on.

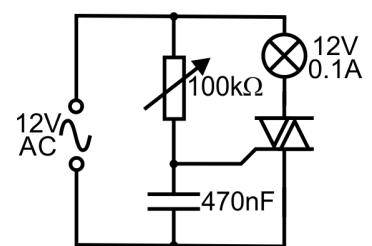
Blue - AC supply
Red - triac

Triac switches on for part of both 'positive' and 'negative' half-cycles but not symmetrically.



Challenge:

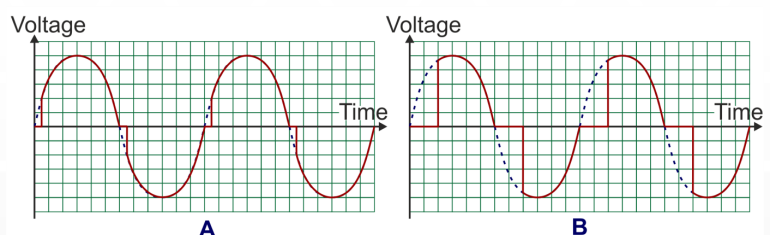
What is the effect of moving the lamp as shown in the second circuit diagram?



Complete the following:

Phase lag increases if the capacitor value or if the resistor value

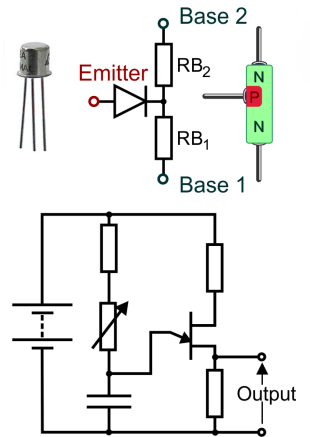
The graphs show two signals across a **lamp** controlled by a triac.
In which is the lamp brighter?



WORKSHEETS

Worksheet 14 - The UJT Relaxation Oscillator

The UJT (unijunction transistor) has only one p-n junction, as its name suggests. However, it has three terminals, two called bases, base 1 and base 2, and one emitter. It consists of a bar of lightly doped n-type silicon, giving it a resistance of a few kilohms, typically. A small p-type area is created towards one end, dividing up the device into two unequal resistors. The equivalent circuit, above, shows this arrangement.

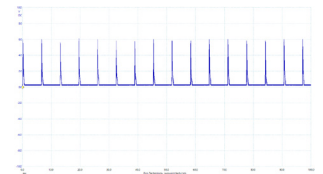


The circuit diagram, opposite, gives the UJT circuit symbol and shows it triggered using phase control. The frequency of the oscillations that result is controlled by the setting of the variable resistor.

The oscillation process:

- Initially, the UJT has a relatively high resistance.
- The capacitor starts charging.
- When the voltage across the capacitor is sufficient, it forward biases the p-n junction and a large current flows into the UJT, to base 1.
- This floods it with free charge carriers, reducing its resistance drastically.
- The capacitor is almost short-circuited and discharges quickly.
- The p-n junction switches off and the process repeats.

The trace opposite shows the appearance of the output signal - a series of sharp spikes, ideal for triggering thyristors and triacs.



The trace opposite shows the appearance of the output signal - a series of sharp spikes, ideal for triggering thyristors and triacs.

Your results:

1st variable resistor setting:

- Amplitude of signal = ...
- Time period of signal = ...

Calculate the frequency of this signal = ...

2nd variable resistor setting:

- Amplitude of signal = ...
- Time period of signal = ...

Calculate the frequency of this signal = ...

Write a step-by-step explanation of why the UJT oscillates.

WORKSHEETS

Worksheet 15 - Lamp Control - UJT and Thyristor

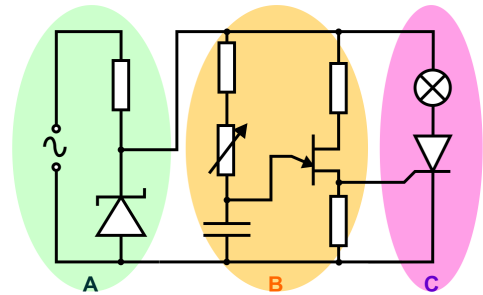
The thyristor is designed to switch currents of hundreds of amps and voltages of thousands of volts. To do so, they must switch on and off extremely rapidly, otherwise so much energy would be dissipated in the thyristor that it would be destroyed.

'Instant' switching requires trigger pulses that rise extremely rapidly. The 'spikes' generated by the UJT relaxation oscillator are ideally suited for this.

Which section of the circuit diagram opposite,

A, B or C, represents:

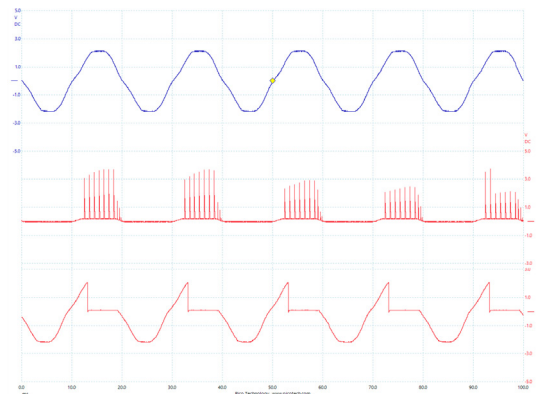
- The UJT oscillator;
- The zener voltage regulator;
- The thyristor switch?



The three traces below were obtained from the circuit investigated here. They show a thyristor triggered by the pulses from a UJT oscillator.

Identify:

- With a label 'P' the region of a trace that shows the thyristor switched on;
- With a label 'Q' the region of a trace that shows the thyristor switched off;
- With a label 'R' the UJT 'spike' that turns on the thyristor;
- With a label 'S' the AC supply waveform.



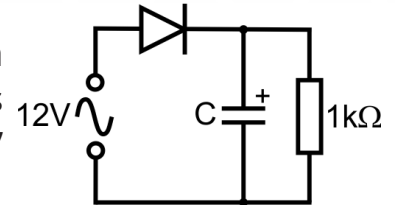
Describe what to do to make the lamp brighter and explain why it happens.

WORKSHEETS

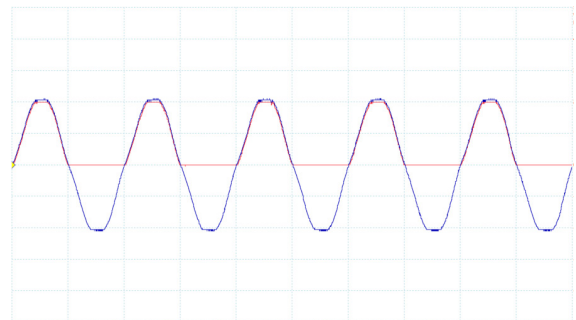
Worksheet 16 - Voltage Conversion - Half-Wave Rectification

Rectification is the process of turning AC into DC, often using a diode. There are several ways to do this. The simplest is the half-wave rectifier.

The circuit diagram shows a diode delivering a DC supply to a load, represented by the $1\text{k}\Omega$ resistor. The capacitor, known as a reservoir or smoothing capacitor, has the job of 'smoothing' (removing voltage variations,) from the DC supply.



The first diagram shows oscilloscope traces for the AC supply voltage and for the output of the half-wave rectifier with no smoothing capacitor.

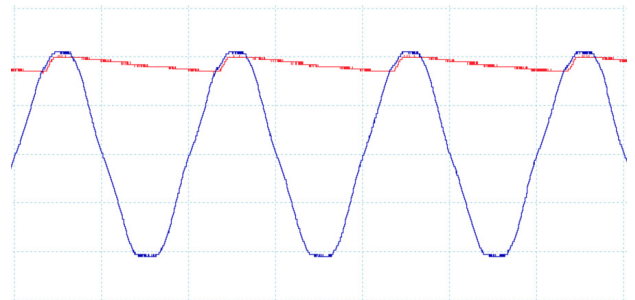


Add labels to identify:

- The AC supply;
- 0V;
- The DC output.

Why do we say that this output is DC?

The next diagram shows the effect of the smoothing capacitor.



Add an arrow to show the size of the ripple voltage.

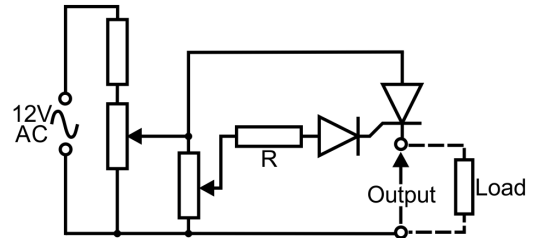
What factors (up to three,) determine the size of the ripple voltage?

WORKSHEETS

Worksheet 17 - Controlled Half-Wave Rectification

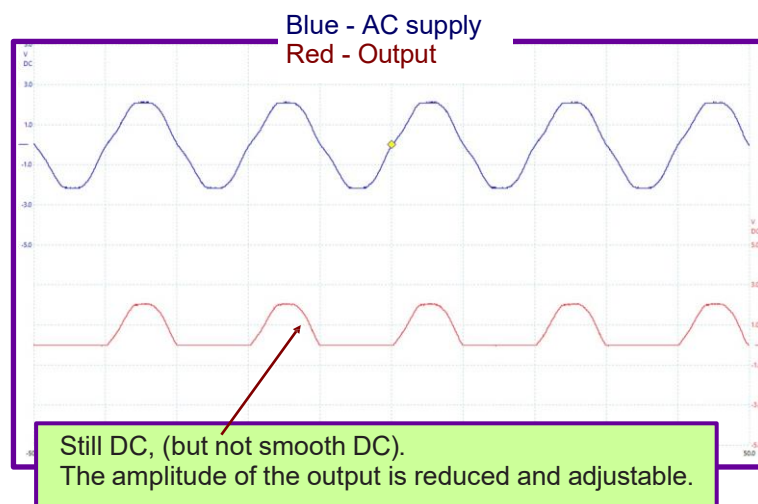
Controlled rectification combines AC to DC conversion with the ability to vary output voltage in order to control the speed of a motor, brightness of a lamp, strength of an electromagnet etc.

The circuit diagram shows one way to do this, using a thyristor - a rectifier with 'one-way' conduction properties.



The next diagram shows the effect of this circuit on the AC supply.

The variable resistor is set to a mid-range value.



Describe what to do to make the lamp brighter and explain why it happens.

Modify the circuit diagram to show how the output can be smoothed by adding a single component.

What is the purpose of resistor R?

Challenge:

Which position of the variable resistor gave the motor maximum speed?

WORKSHEETS

Worksheet 18 - Voltage Conversion Full-Wave Rectification

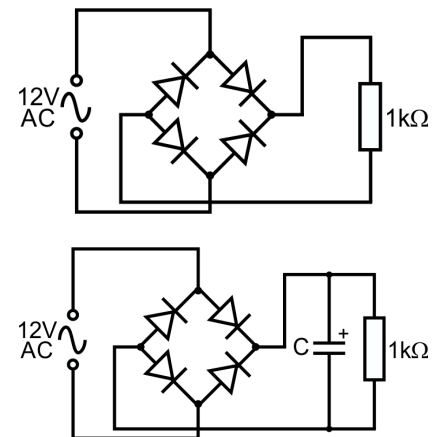
A half-wave rectifier uses only one diode, but does not make efficient use of the electrical energy on offer. For half of the time, no current at all flows through the load.

A full-wave rectifier overcomes this limitation, but uses a number of diodes to do so, and so drops more of the AC voltage across them.

The diagram shows a full-wave rectifier using four diodes.

Remembering how to draw the circuit:

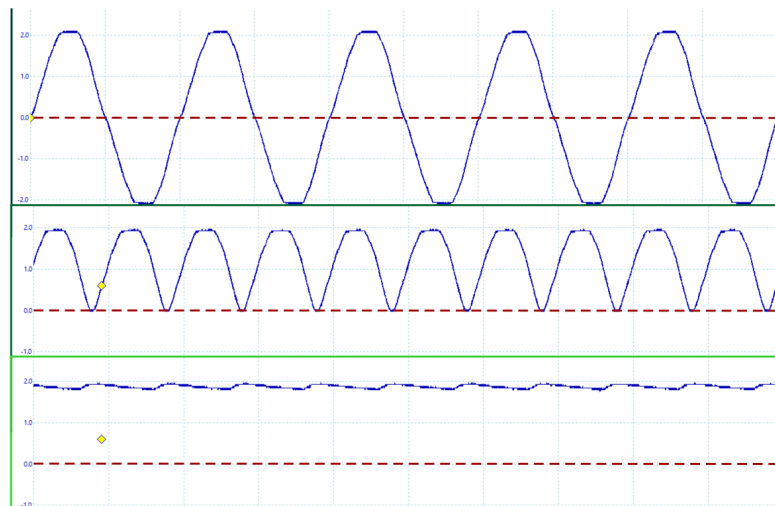
Notice that current flowing from the AC supply is given a choice. The diodes it reaches first are connected different ways round. Diodes on opposite sides of the square face in the same direction.



As with half-wave rectification, the DC output can be smoothed by adding a capacitor in parallel with the load.

The next diagram is a composite made from three oscilloscope traces:

- The AC supply;
- The full-wave output;
- The full-wave output with smoothing.



On each , a red dotted horizontal line has been added to show the position of 0V.

The full-wave output:

- Is DC;
- Has twice the frequency of the half-wave waveform.

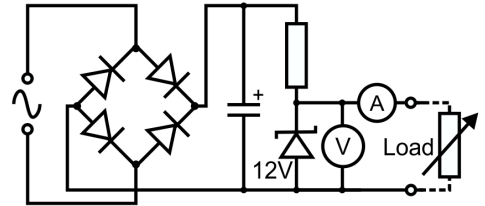
WORKSHEETS

Worksheet 19 - The Zener Diode Voltage Regulator

A power supply converts AC electricity into DC and delivers a steady voltage no matter what. In it, a voltage regulator maintains a steady output voltage over a range of output currents. At its core is a zener diode, which can deliver a range of currents with little change in the voltage across it.

In the circuit used in the investigation:

- The full-wave rectifier converts the AC supply to DC;
- A capacitor then smoothes the ripple voltage;
- A zener diode voltage regulator supplies current to a variable resistor, representing the load connected to the power supply. Adjusting it changes the output current delivered.



Your results:

I_{LOAD} in mA	0	5	10	15	20	25	30	35
V_{OUT} in V								

The aim is to keep V_{OUT} constant to within 100mV (0.1V). Use your graph of V_{OUT} against I_{LOAD} to estimate the maximum output current possible with this constraint.

Maximum output current = ...mA

The analysis goes like this:

- The supply has a peak voltage of $12 \times \sqrt{2} = 17.0V$.
- Voltage drop across the bridge rectifier = $\sim 2 \times 0.7 = \sim 1.4V$, giving a DC supply voltage to the voltage regulator of $V_S = \sim 15.6V$.
- Voltage across zener diode = 12V, leaving $15.6 - 12 = \sim 3.6V$ across resistor R.

Power rating of zener diode = 500mW maximum, (from Locktronics Technical Guide). Using ' $I = P/V$ ', **maximum** current through zener diode (and resistor R) = $500/12 = 41.7mA$. Using ' $R = V/I$ ', **minimum** value of $R = 3.6/41.7mA = 86.3\Omega$. The investigation used 220 Ω .

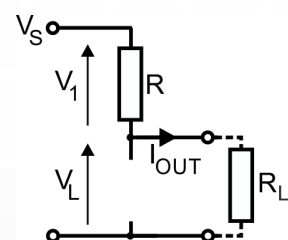
When 3.6V is dropped across it, current through it = $3.6/220 = 16mA$. This dissipates $16 \times 12 = 196mW$ in the zener diode - less than the maximum power rating!

To keep the zener diode in reverse breakdown, it needs to pass a current of at least 5mA (from Locktronics Technical Guide). Hence, the maximum permissible output current, $I_{OUT} = 16 - 5 = 11mA$.

If the output current is greater, then the zener diode comes out of reverse breakdown. It behaves like a 'normal' reverse-biased diode and stops conducting. The circuit then behaves like the one shown opposite - a straightforward voltage divider:

The voltage V_L across the load is then given by:

$$V_L = \frac{V_S \times R_L}{R + R_L}$$



WORKSHEETS

Worksheet 20 - The 7805 Voltage Regulator

The language of voltage regulation:

Ideally, regulation comes in two forms:

Line regulation - the **output voltage** is immune to changes in the **input (line) voltage**.

Load regulation - the **output voltage** is immune to changes in the **output current**.

There are two categories of voltage regulator - **linear** and **switching**.

- **Linear** regulators sense changes in output voltage. A feedback loop adjusts the output current to try to return the output voltage to its preset value.
- **Switching** regulators use the ability of capacitors and inductors to store electrical energy. By switching the electricity supply to these devices on and off rapidly, the voltage across them is controlled over a range of output currents.

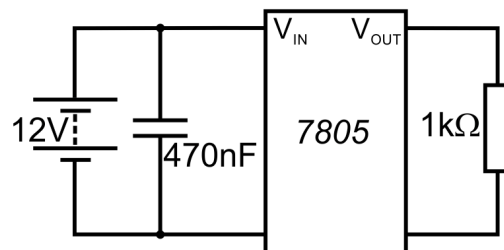
	Linear	Switching
Action	Step-down (buck) only	Step-up (boost) OR step-down (buck)
Efficiency	Low-depends on ($V_{IN} - V_{OUT}$)	High
Component count	Low	High
Size	Small (without heat-sink)	Large
Noise	Low	High - due to rapid switching
Cost	Low	High

The 7805 is a linear voltage regulator, part of the '78XX' regulator series, (in which the last two digits indicate the output voltage.) The circuit used to investigate its behaviour is shown below:

Your results:

Part 1:

- Input voltage, V_{IN} = ... V
- Input current, I_{IN} = ... mA
- Output voltage, V_{OUT} = ... V
- Output current, I_{OUT} = ... mA



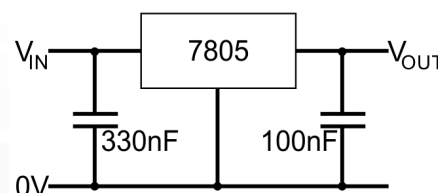
$$\begin{aligned} \text{Power efficiency} &= (\text{Output power} / \text{Input power}) \times 100\% \\ &= (V_{OUT} \times I_{OUT} / V_{IN} \times I_{IN}) \times 100\% \\ &= \% \end{aligned}$$

Part 2:

V_{IN} in V	3	4	5	6	7	8	9	10
V_{OUT} in V								

What is the lowest input voltage that produces the expected output voltage

The circuit diagram on the previous page includes a capacitor to reduce noise on the power supply lines. In practice, it is also advisable to use a second capacitor to filter noise on the output of the regulator, as the circuit diagram opposite shows. The values shown are the minimum to ensure stability.



WORKSHEETS

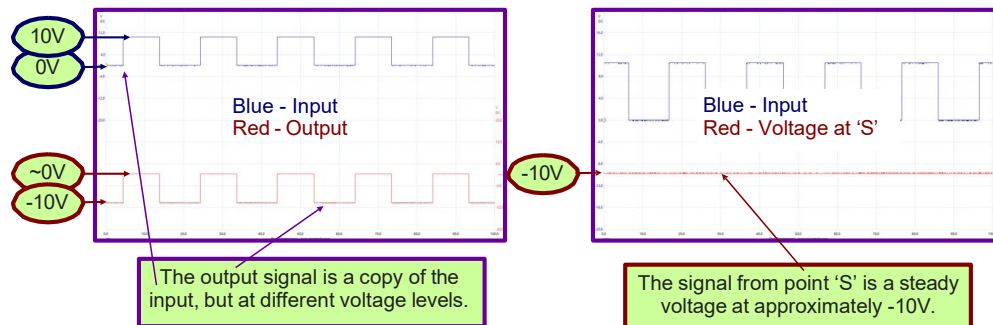
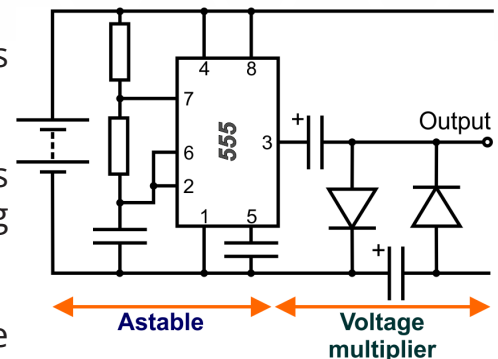
Worksheet 21 - The Level Shifter:

The circuit consists of two sections:

- An **astable** - turns DC into a square wave output;
- The **voltage multiplier** - changes the voltage levels of the output.

Using only capacitors and diodes, voltage multipliers can step up low voltages to high values while being lighter and cheaper than transformers.

The traces show the action of the astable and voltage multiplier.



The analysis - (assuming ideal component characteristics):

Capacitors -

- Keep the same voltage **drop** across them until a current has had time to deposit or remove charge from the plates.
- A voltage step affects each plate equally. as there has been no time for a flow of charge to take place i.e. if one plate rises by 10V, then so does the other.

Point P -

- Follows the square wave signal i.e. 0V then 10V etc.

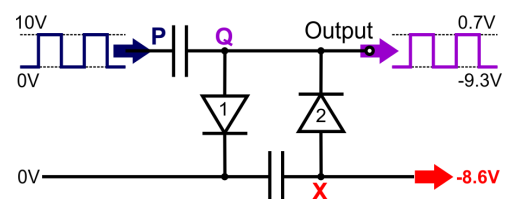
Point Q -

- As square wave voltage rises from 0 to 10V: The voltage step passes straight through the capacitor. The voltage at Q tries to rise to 10V, but diode 1 is forward-biased and clamps it at +0.7V.
- As square wave voltage falls from 10 to 0V: The voltage step passes through the capacitor. The voltage at Q falls by 10V, to -9.3V.

The output signal is the signal at Q - a square wave oscillating between -9.3V and +0.7V.

Point R -

- When Q = -9.3V, diode 2 is forward-biased. R sits at 0.7V above Q, i.e. -8.6V.
- When Q rises to +0.7V, diode 2 is reverse-biased. If no output current flows, the voltage at R is held at -8.6V.

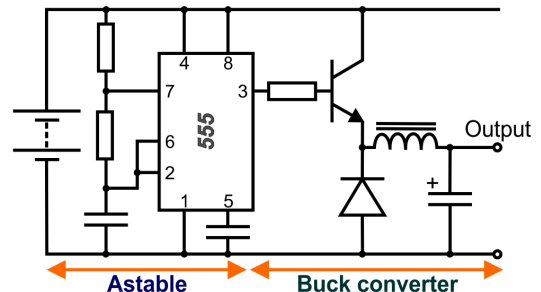


WORKSHEETS

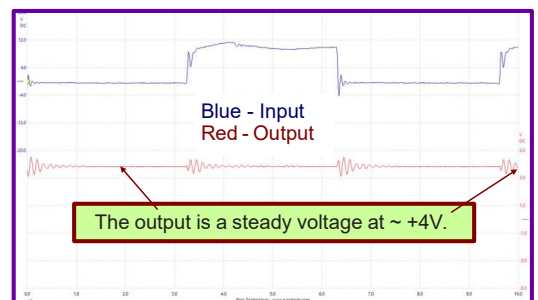
Worksheet 22 - The Buck Converter

A form of SMPS (switched-mode power supply,) a 'buck' converter is a DC-to-DC converter which steps **down** the voltage, so that its output voltage is smaller than its input voltage and does so with little energy loss.

The circuit diagram shows a simple buck converter driven with pulses from a 555 astable. The transistor buffers the astable from the output, reducing the current taken from the 555 IC.



The traces, obtained from the circuit, show a steady 4V output. They also show 'ringing' in response to the sudden steps in voltage produced by the square wave, caused by stray capacitance and inductance in the circuit.



The analysis:

It's all down to the behaviour of **inductors and capacitors**.

Inductors hinder rapidly changing voltages (like AC).

The higher the frequency, greater the hindrance. They generate a magnetic field inside the coil.

A quandary:

No current, no magnetic field - no magnetic field, no current!

In reality, current and magnetic field build slowly, storing energy in the magnetic field. When the external current stops, the magnetic field collapses, generating a current in the same direction.

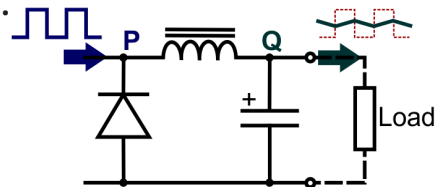
Capacitors block DC currents, but offer little hindrance to high frequency AC.

The quandary - they generate an electric field across the plates as the voltage rises - generate a voltage across the plates as the electric field rises.

In reality, both build together, storing energy in the electric field. When the external voltage stops, the capacitor acts as a 'battery' to replace it, using energy stored in the electric field.

Challenge:

How can you test whether the output is load regulated?

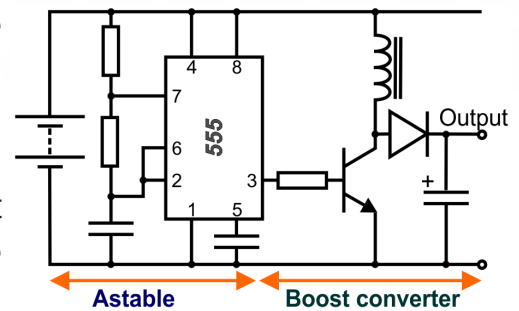


WORKSHEETS

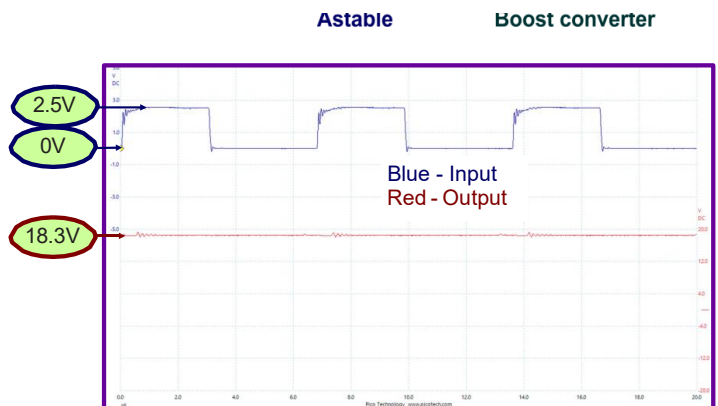
Worksheet 23 - The Boost Converter

A 'boost' converter, another form of switched-mode power supply, steps **up** the **voltage**, but steps **down** the **current**, to satisfy the conservation of energy law.

The DC output voltage is bigger than the DC input voltage, but the output current is smaller than the input current.



These traces, obtained from the boost converter circuit, show a steady 18.3V output signal.

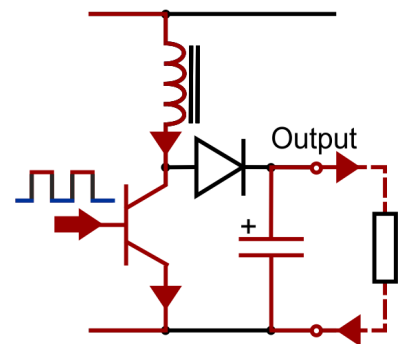


The analysis:

Its still down to the behaviour of **inductors** and **capacitors**.

When the astable signal is **high**:

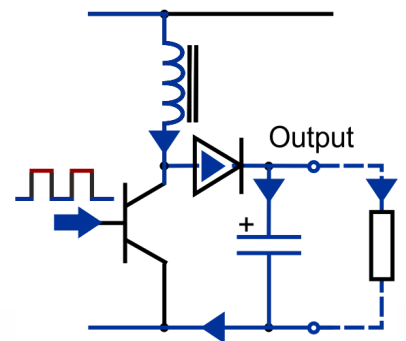
The transistor is on and very low resistance path to 0V opens. Current flows through the inductor, storing energy in the magnetic field. The diode is reverse biased. The electric field in the capacitor collapses as it 'funds' a current through the load.



When the astable signal is **low**:

The transistor turns off.

The diode is forward biased and energy stored in the inductor's magnetic field drives a current that both supplies the load and tops up the charge on the capacitor (storing energy in its electric field).



Challenge:

"The transistor buffers the astable from the output...", Explain what this means

WORKSHEETS

Worksheet 24 - 555 Inverter

Inversion, DC to AC conversion, is an important technique in a number of areas:

- Feeding the DC output of solar panels into the National Grid;
- Powering emergency lighting from batteries in public buildings;
- Creating variable frequency power supplies to control the speed of AC motors.

Inverter circuits can be simple or complex, depending on the output required.

A basic low power AC supply, for lighting, for example, can use an inverter as simple as an astable. Its output can be stepped up or down by a transformer to give the voltage needed.

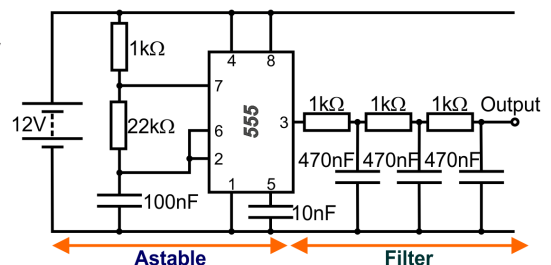
At the other extreme, for audio equipment, for example, a more sophisticated circuit involving filtering stages is used to obtain a sinusoidal supply to avoid an audible hum on the equipment.

According to Fourier's theorem, a signal like a square wave can be created by combining a series of sine waves of different frequencies and amplitudes. (A sine wave is considered to be the simplest signal, as it contains only one frequency of oscillation.)

A spectrum analyser decomposes a signal to reveal these components. Its output is a graph showing frequency on the horizontal axis and amplitude on the vertical axis. Each 'spike' on the graph represents a sinusoidal signal. The lowest frequency component, called the fundamental, represents a sinusoidal signal with the same frequency as the square wave.

In this investigation, the inverter circuit consists of two sections:

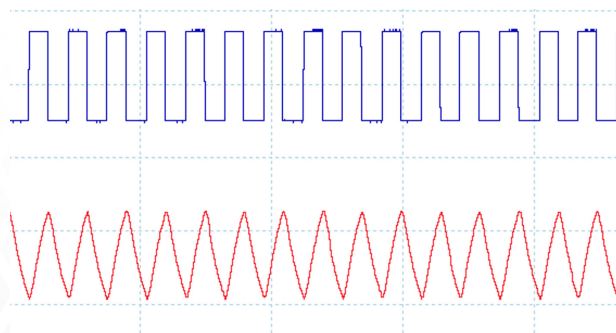
- An **astable** - turns DC into a pulsing square wave output;
- A **filter** - removes high frequency square wave components, leaving a sine wave.



Both can be identified in the circuit diagram for one form of inverter, based on a 555 timer.

If the low-pass filter removed all components with frequencies higher than the fundamental, the output would be a sinusoidal signal with the frequency of the square wave.

The following trace shows the output of the astable and the almost sinusoidal signal emerging from the filter!



This image shows a blank sheet of white paper with horizontal ruling lines. The lines are evenly spaced and extend across the width of the page. At the bottom of the page, there is a decorative border consisting of a repeating pattern of light gray hexagons. The overall appearance is that of a clean, unused piece of stationery or notebook paper.

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