locktronics

Simplifying Electricity

Power and energy electronics

CP3666

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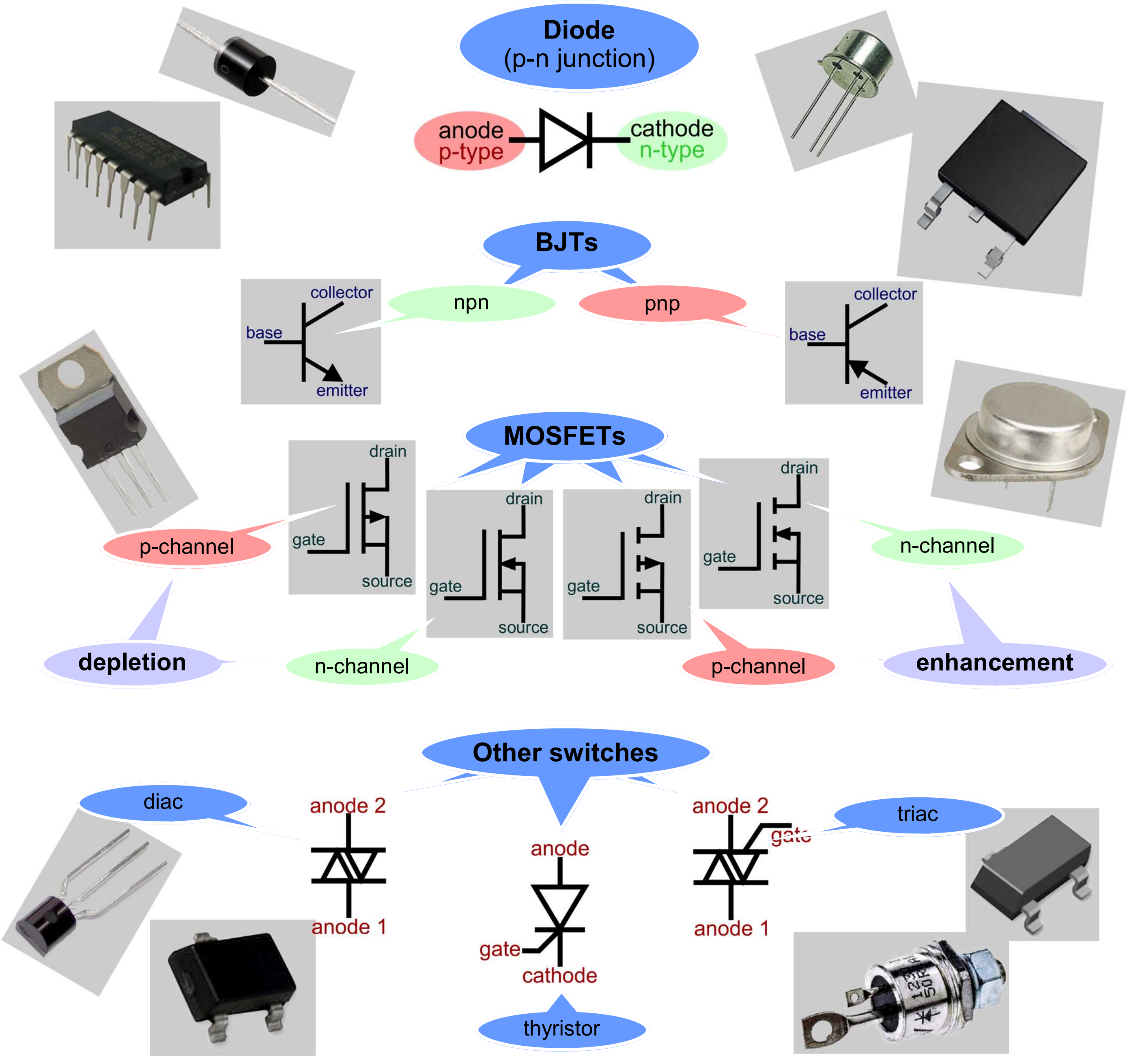
Contents

Introducing the components



The hardware:

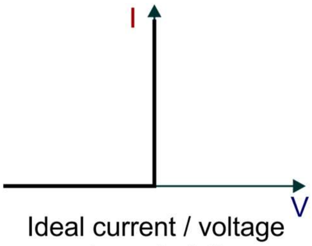
- Semiconductors used in the electronics industry come in two types, n-type or p-type, depending on which impurities are diffused into the crystal, usually silicon.
- A p-n junction is a single semiconductor crystal where one end is p-type and the other n-type. Its distinctive properties are exploited 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.

Diodes:

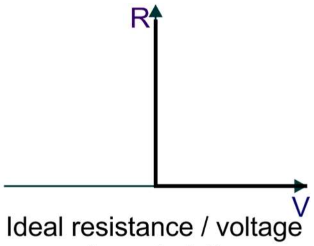
As the name suggests, these have only two terminals, the anode and cathode.

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:



Ideal current / voltage characteristic



Ideal resistance / voltage characteristic

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;
- LEDs - light-emitting diodes convert electrical energy into light at very high efficiency;

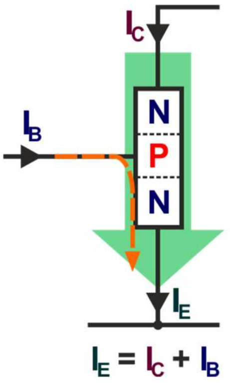
Bipolar junction transistors (BJT):

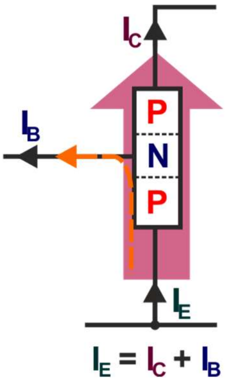
come in two types, npn or pnp, depending on the way in which the impurities are added.

- 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 trminals.

- 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.

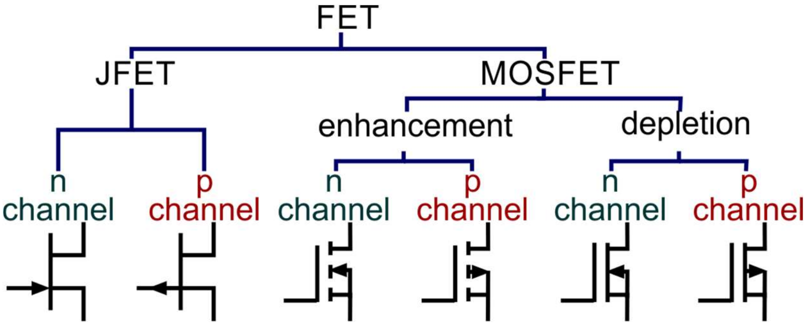
  Since the base current is much smaller than the collector current, the emitter current and collector currents are roughly equal.





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.

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.

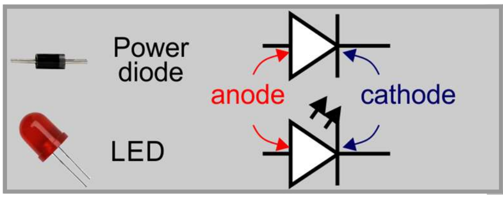
An important issue! These components are mass-produced. As a result, their properties vary. The circuits shown in this course function for the vast majority of components. Occasionally, be prepared to vary the odd resistor or capacitor value to optimise the performance of the circuit. ***Consult your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

Worksheet 1

The p-n junction diode

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.

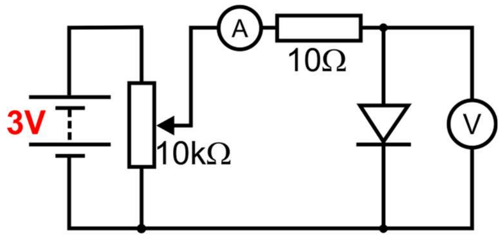


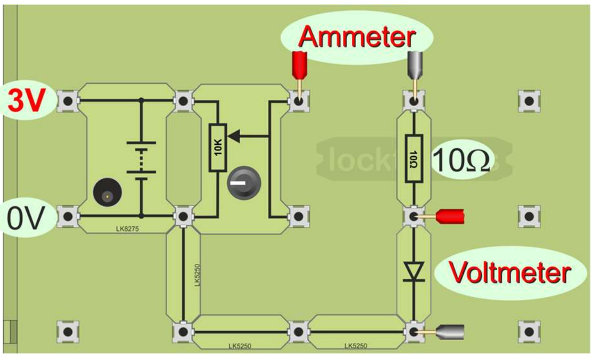
The cathode is marked by a stripe on the body.

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!

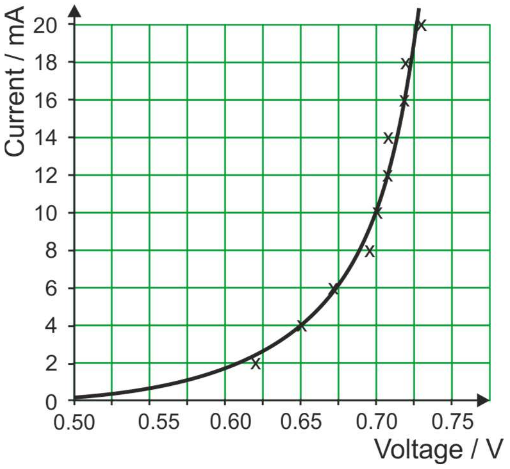
  Be careful - turn the knob on the variable resistor very gently!
- Continue in this way, increasing the current in 2mA steps, up to 20mA, taking the voltage reading each time.
- Write your results in the table given in the Student Handbook.

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.

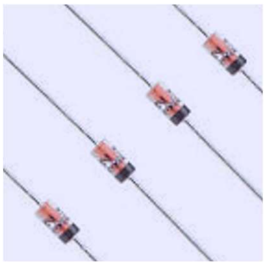
Challenge:

- 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.

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.

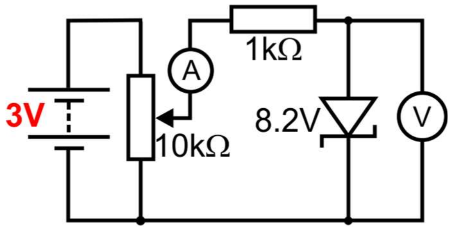


Over to you:

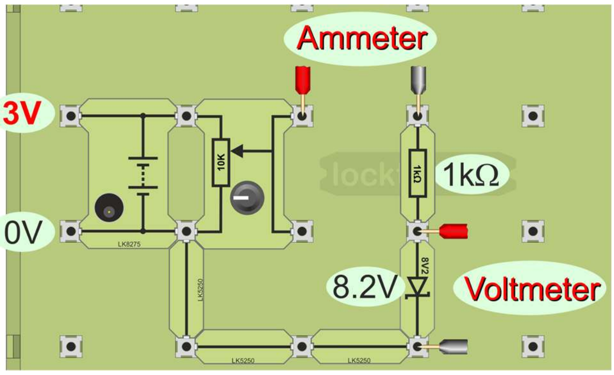
Part A - Under forward bias:

- 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 anti-clockwise 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 180^0 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.

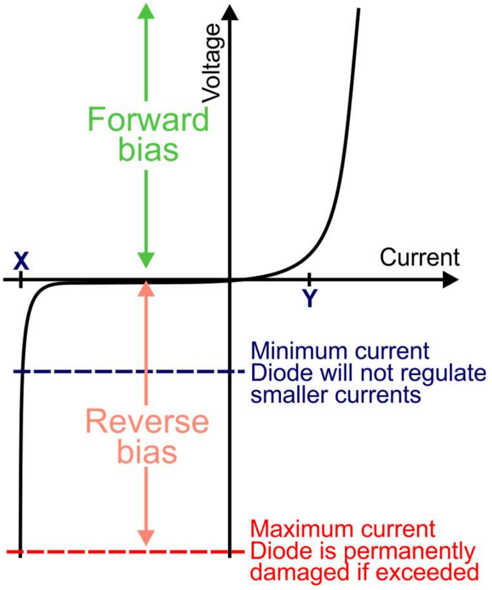
Worksheet 2
The zener diode

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 = 303mA.

Typical application - a reference voltage source:

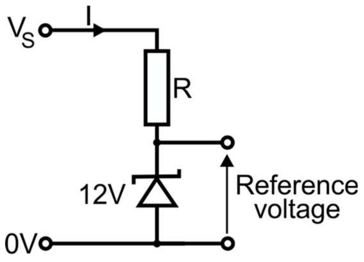
As the graph shows, the voltage across a zener diode in reverse breakdown changes very little as the current changes. This makes it very useful as a constant voltage source in a number of applications, such as ADCs (analogue-to-digital converters) and DACs (digital-to-analogue converters).

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: $V_S = 15V$, $R = 300\Omega$



The voltage across resistor R = $V_S - V_Z$ = 15 - 12 = 3V.
Applying Ohm's law to the resistor,
current I = V / R = 3 / 300 = 0.01A = 10mA.

Power dissipated in the zener diode = V_Z x I = 12 x 10 = 120mW.

Power dissipated in the resistor = V x I = 3 x 10 = 30mW.

Worksheet 3

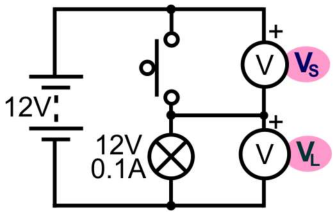
On/Off control - BJT switch

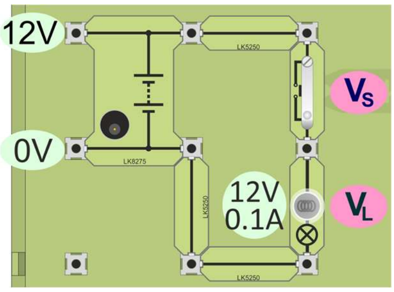
The module begins by looking at on/off control of electrical devices, switched using a variety of electronic components.

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).



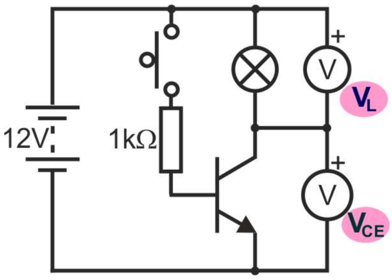


- Build the first circuit, where a push-switch controls a lamp.
- Set the DC power supply to output 12V.
- Measure the voltage, V_S, across the switch:
    - when the switch is open;
    - when it is closed.

  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.

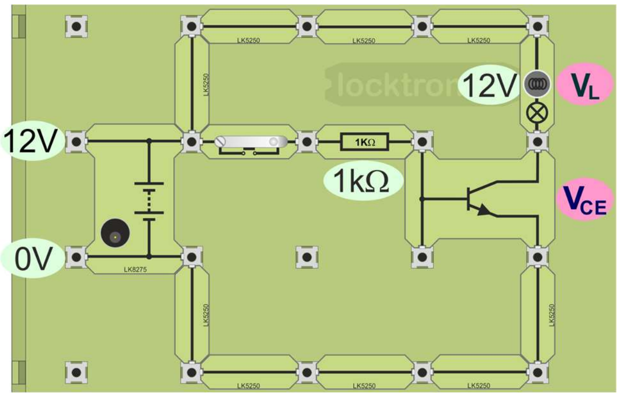
- Build the second circuit, where a transistor controls the lamp.

  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.



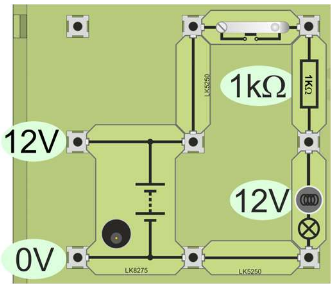
Worksheet 3
On/Off control - BJT switch

So what?

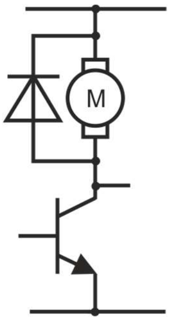
- Look at the results for the second part of the investigation.
  - Add together V_{CE} and V_L. What do you notice?
  - What do you expect, bearing in mind that the transistor and lamp form a voltage divider across the power supply?
- The behaviour is the same as for the mechanical switch. The transistor 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 1kΩ 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 1kΩ 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.*

Worksheet 4

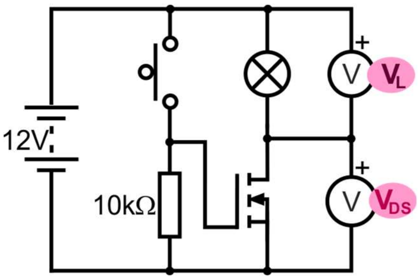
On/Off control - MOSFET switch

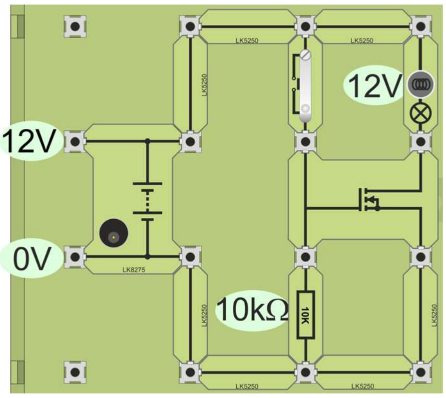
The BJT switch is a current-controlled device. The collector-emitter resistance depends on the base current

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:

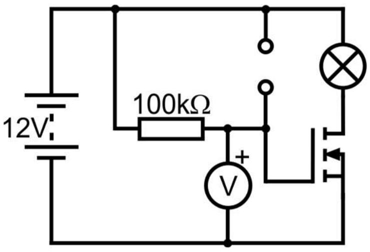
- Build the circuit shown below and set the DC power supply to output 12V.
- Measure voltages **V_L**, across the **l**amp and **V_{DS}**, between **d**rain and **s**ource of the MOSFET when the switch is open and when closed.
- Write your results in the table in the Student Handbook.





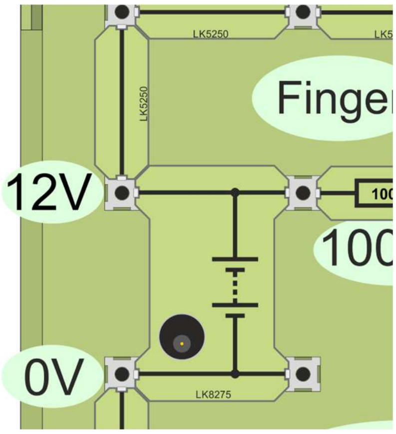
The next circuit illustrates the principle of the touch switch, a common MOSFET application.

- 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.



Worksheet 4

On/Off control - MOSFET switch

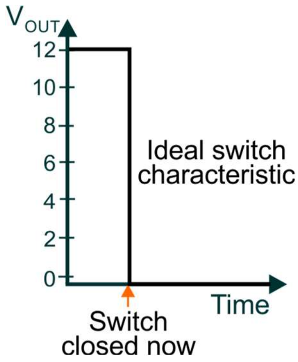
So what?

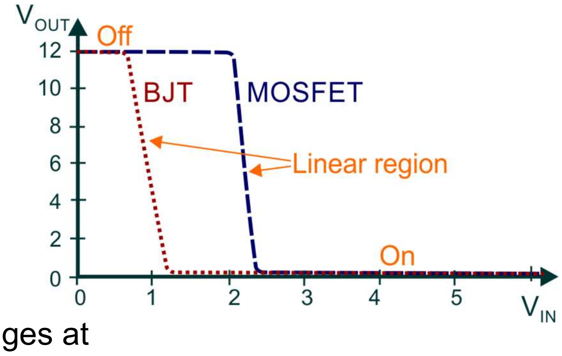
The enhancement-mode MOSFET:

- It is "Off" when the gate bias voltage is zero.
- A drain current flows only when the gate voltage (V_{GS}) is greater then 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_{DSON} .

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** x **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.

Worksheet 5

On/Off control - thyristor switch

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

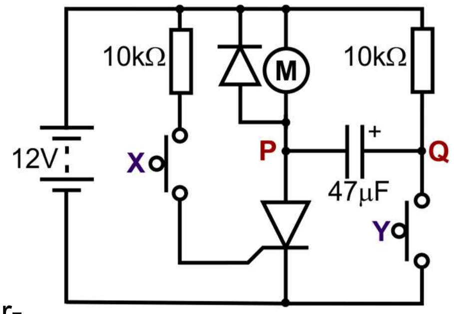
They are self-latching - once turned on, by a sufficiently large pulse of current flowing into the gate, they stay on, as long as:

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

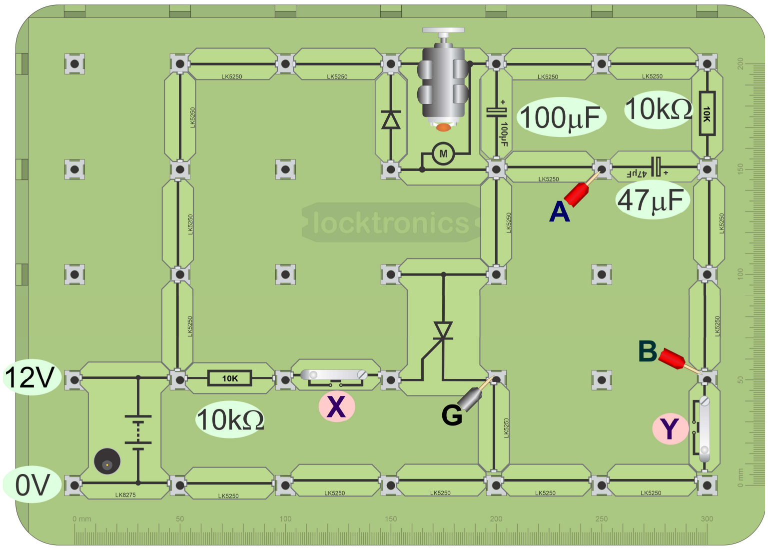
They make superb high-power switching devices because they move extremely quickly from the *forward-blocking* state, (forward-biased, but **not** conducting,) into the *conducting* state. As a result, they dissipate very little power in the process.

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 100µF capacitor to reduce noise which can prevent the thyristor latching on (not shown in the circuit diagram, - ‘officially’ it is not needed.)
  - a 10kΩ 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.

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 ~ 1 mA,);
- **and** the voltage between gate and cathode, V_G, exceeds the **minimum gate voltage,** V_{GT}, (typically ~ 0.8V,)

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 ~ 10mA.

When conducting, a residual voltage drop of ~ 1V 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, **g**ate-**t**urn-**o**ff, 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.

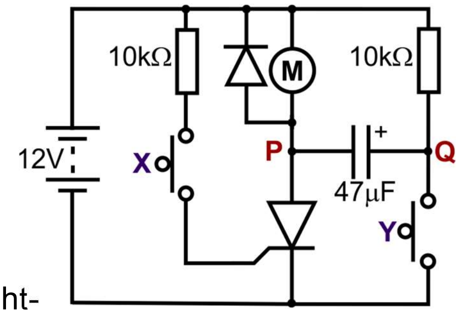
The usual way to switch it off in a DC circuit is to use **capacitor commutation**.

When switched **off**:

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

Closing switch **X:**

- sends a current into the gate, switching **on** the thyristor;
- the voltage at **P** drops to ~ 0V 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** = +12V still.



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

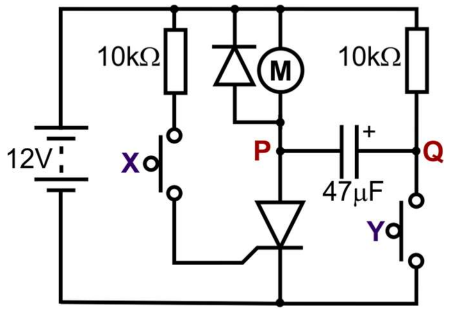
Put another way, **Q is 12V higher than P**.

Worksheet 5
On/Off control - thyristor switch

So what?

Capacitor commutation...:

To switch off the thyristor, press switch **Y:**



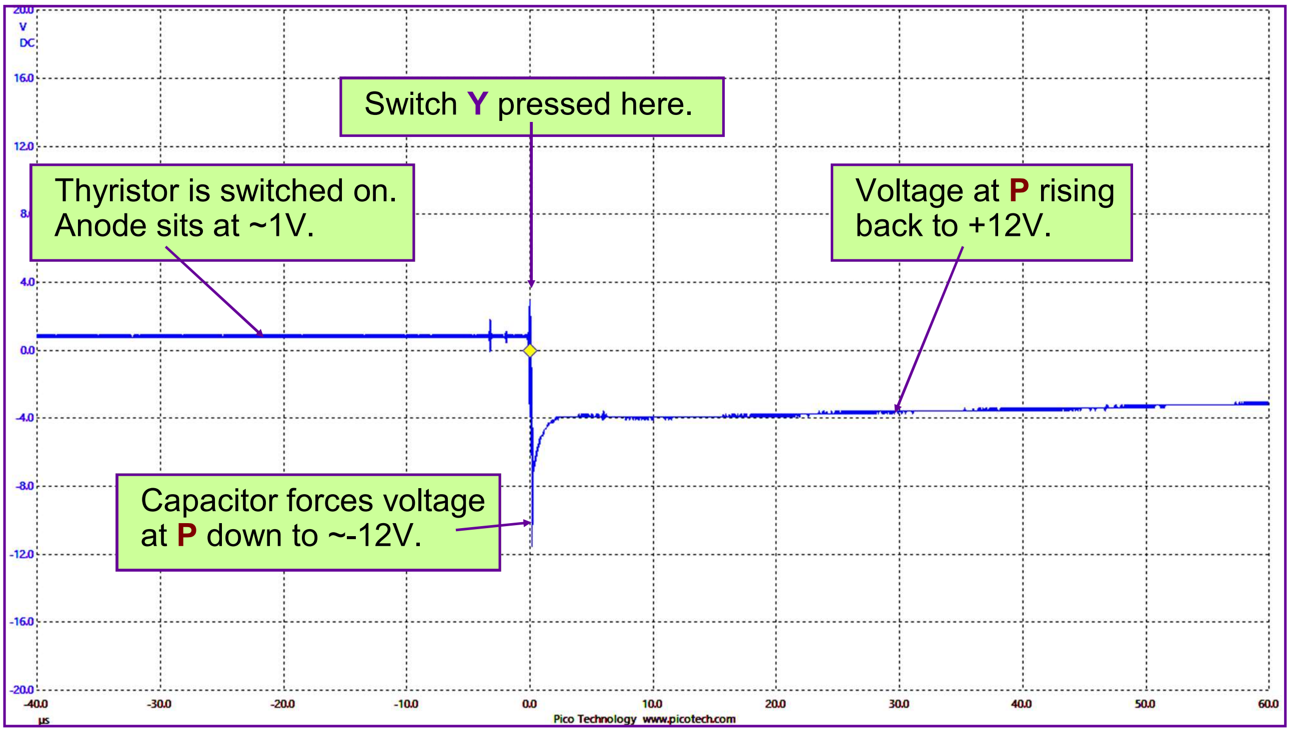
- the voltage at **Q** falls **suddenly** to 0V.

  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:



Worksheet 6

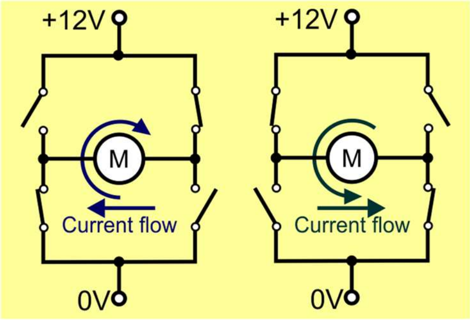
On/off/direction control - H-bridge

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!

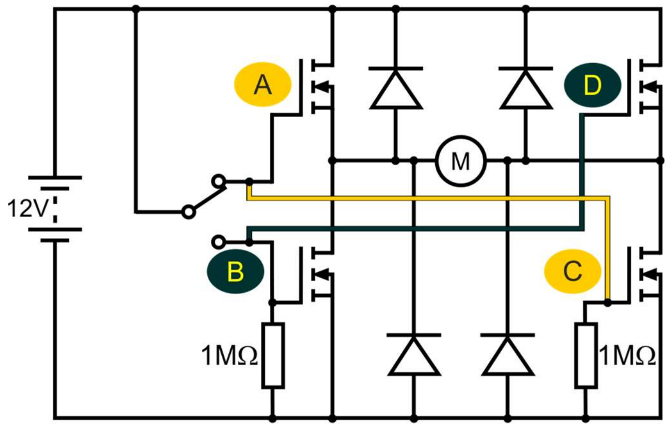
One problem - the power supply will be short-circuited if the wrong pair of switches is closed! The following investigation uses a changeover switch to avoid this.



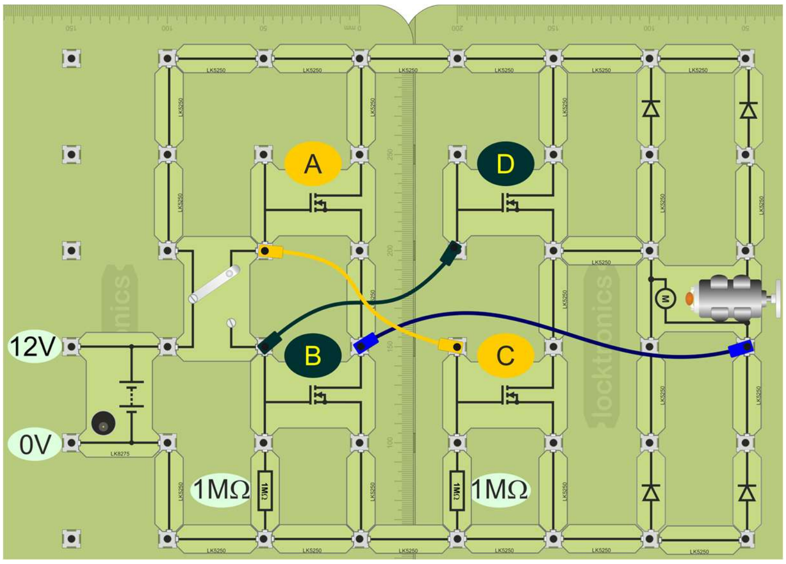
Over to you:

- 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 1MΩ resistors;
  - either:
    MOSFETs A and C are on,
    or
    MOSFETs B and D are on,

  depending on the changeover switch position.



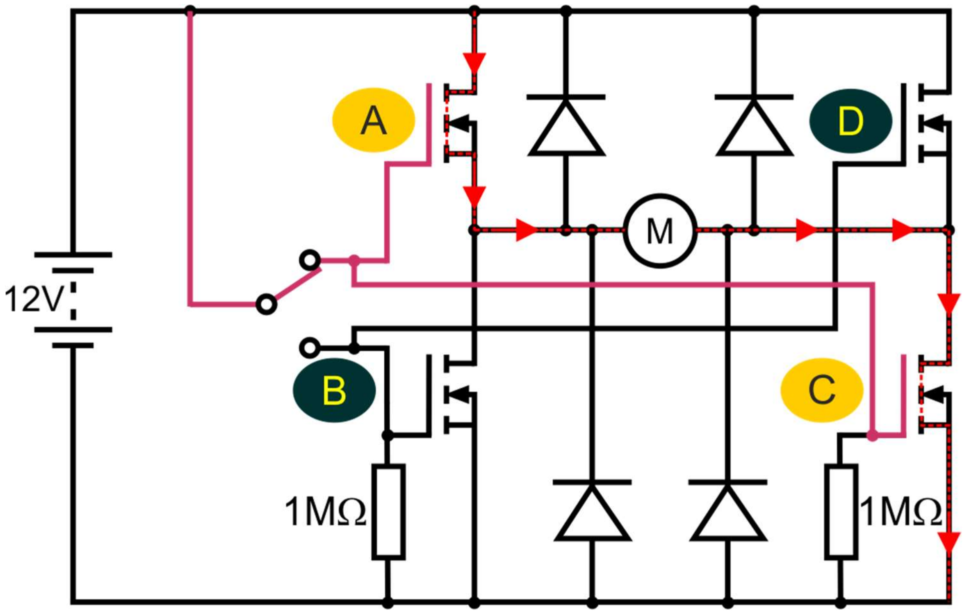
- Set the DC power supply to 12V and switch it on.
- Notice the effect of moving the changeover switch to:
  - the upper position;
  - the lower position;
  - mid-way between them.
- For each position, measure the voltage on the left end of the motor, (drain of C) and on the right end (drain of B).
-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



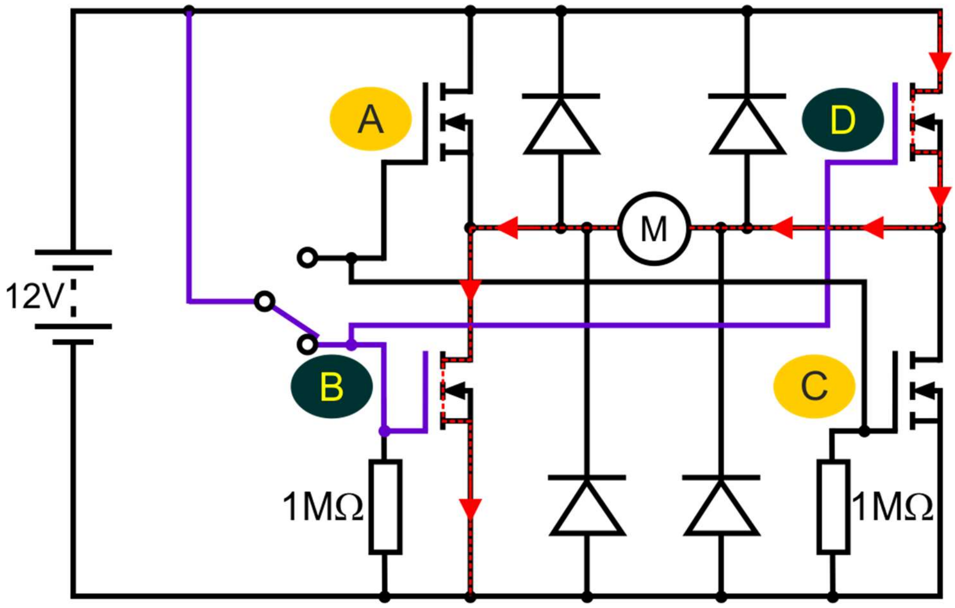
NB: don’t forget to wire the blue lead between the drain of B and the motor.

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.



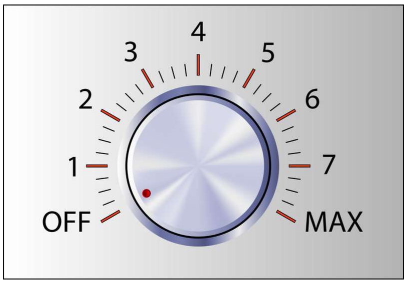
MOSFETs A and C are 'on' and current flows from left to right through the motor.



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

Worksheet 7

Motor control - BJT emitter follower

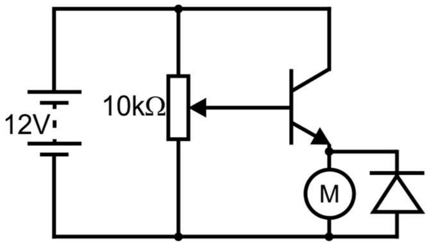


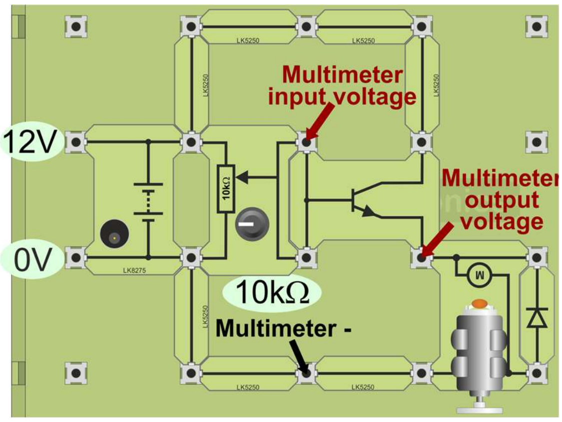
The circuits studied so far offer 'on/off' control. Sometimes, that is not enough. We might want to speed up or slow down a motor,
increase or decrease the brightness of a lamp etc. Then we need graduated control.

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.

Worksheet 7

Motor control - BJT emitter follower

So what?

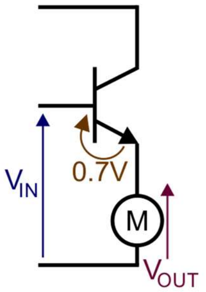
This circuit is useful as an interface between an input device that can supply only a small current and a subsystem that draws a much larger current.

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 ~0.7V, the transistor starts to conduct.
- As a result, a voltage drop of ~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:

$$\text{Voltage gain} = V_{OUT} / V_{IN}$$
$$= \sim 1$$

Current gain:

Output current through load = emitter current I_E

Input current = I_B

Current gain = output current / input current

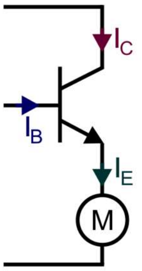
$$= I_E / I_B$$

From Kirchhoff's current law:

$$I_E = I_C + I_B$$

and $$I_C >> I_B$$

Hence current gain = $\sim I_C / I_B = \sim h_{FE}$ (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:

Voltage gain = 0.8

Current gain = 135

Hence **Power gain = 108**

Challenge:

Repeat the measurements for an input voltage of 5.0V.

Is there any effect on the power gain?

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.

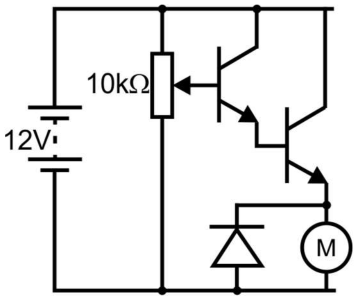
One solution is to couple two transistors together in an arrangement known as a darlington pair - rather like on a railway where they couple together two engines when there is a heavy load to pull!

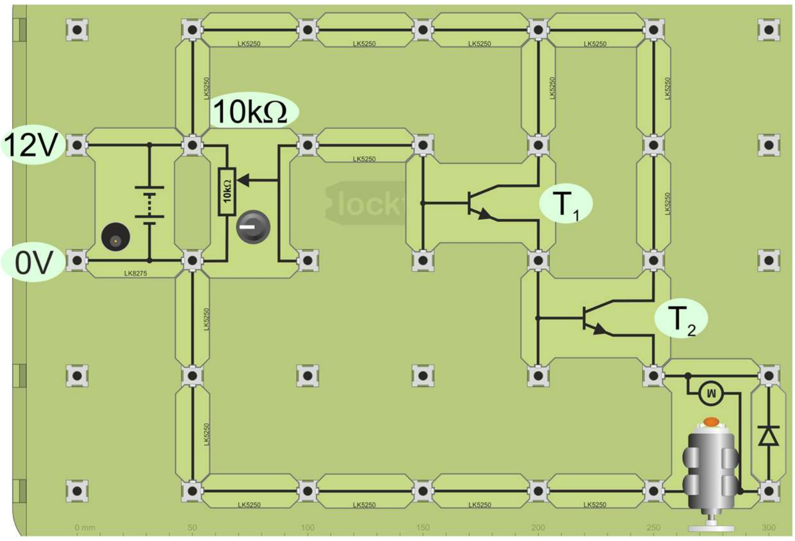
Over to you:

- 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.

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.

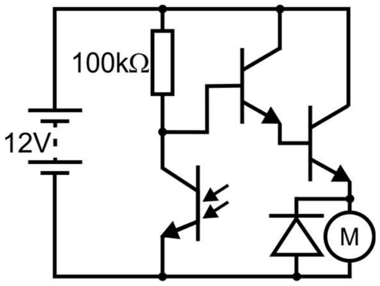
(For a given output, the input current is tiny, as if the subsystem had a huge impedance.)

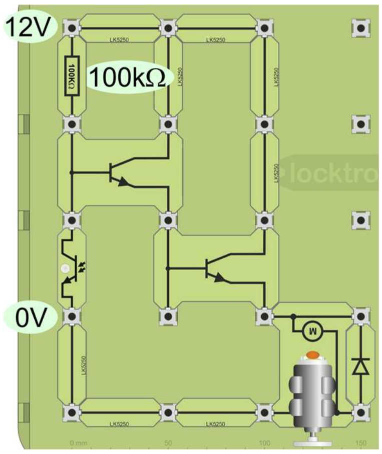
Disadvantages of the Darlington pair follower:

- 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 100kΩ 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.

Worksheet 9

Motor control - MOSFET source follower

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

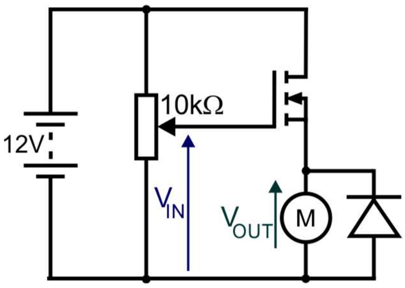
- higher input impedance - less current required to operate it;
- smaller power loss - the effect of the residual resistance, $R_{DS(ON)}$, of the MOSFET is usually smaller than that of the BJT forward voltage drop V_{CE} (~ 0.3V) when the devices are switched on;
- faster switching - conduction by majority,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

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

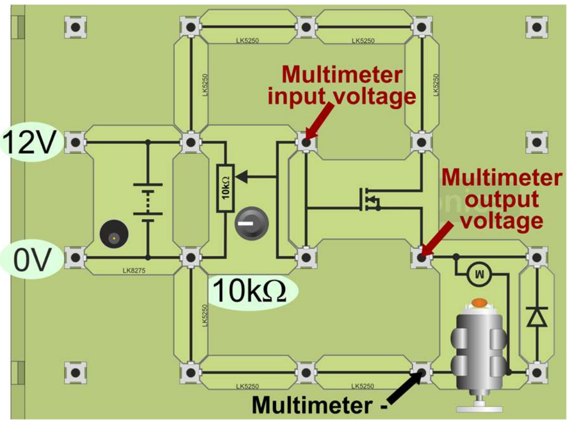
Over to you:

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, $\mathbf{V_{OUT}}$.
- Record the measurements in the table given in the Student Handbook.



- Compare the behaviour of the emitter follower and source follower.

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_G	0.1mA
Output current I_D	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?

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.

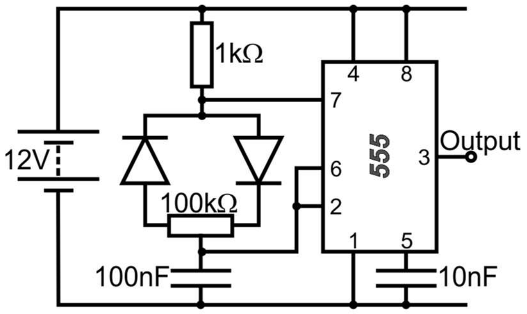
One way to generate and control PWM uses a 555 timer IC.

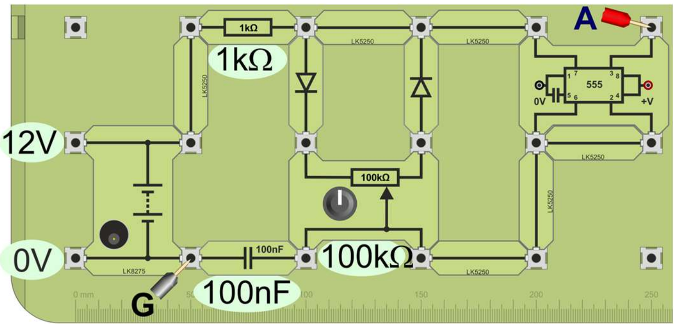
Over to you:

- 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 anti-clockwise.
- Answer the questions in the Student Handbook.



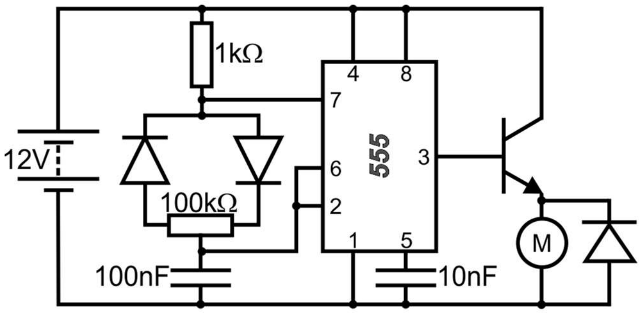


NB: power/gnd connections of 555 timer not shown in layout.

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’.

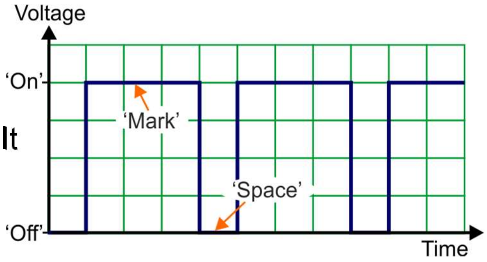


Worksheet 10

Motor control - PWM

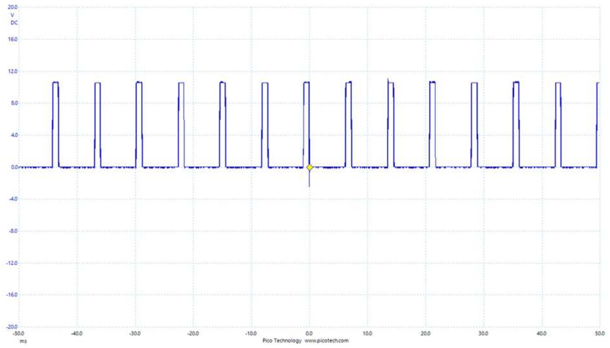
So what?

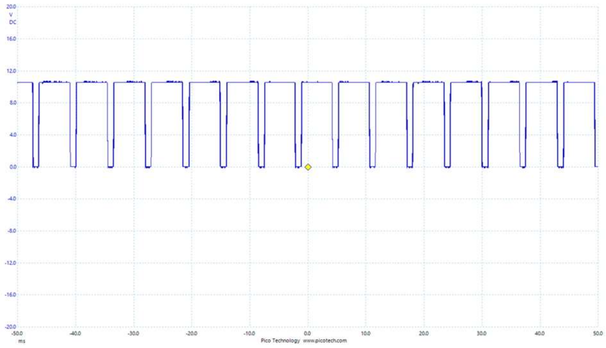
In pulse-width modulation, the output signal switches on and off rapidly and repeatedly.
The ‘mark’ is the time for which it is ‘on’.
The ‘space’ is the time for which it is ‘off’.
The signal shown has a mark-to-space ratio of 3:1.
The term ‘duty cycle’ is another measure of the same thing. It is defined 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 smoothes 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:

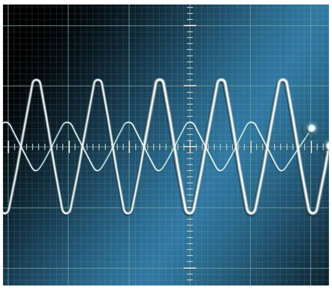
- Using the 100nF capacitor in the circuit, measure the time period for the signal.
- Hence calculate the frequency of the signal.
- Investigate the effect of changing the 100nF capacitor for other similar values.
- Record your conclusions in the Student Handbook.

Worksheet 11

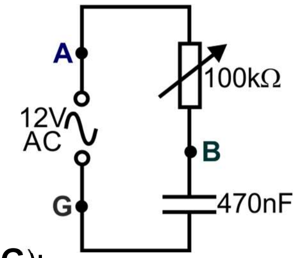
Phase control

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.

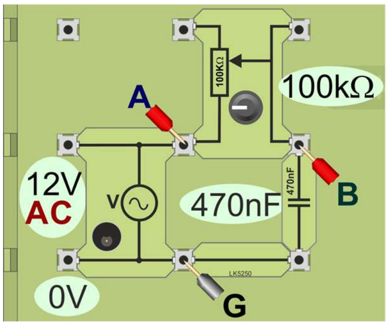


Over to you:



- 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 anti-clockwise.



Suitable Picoscope settings:	
Input range: A and B	+/-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.

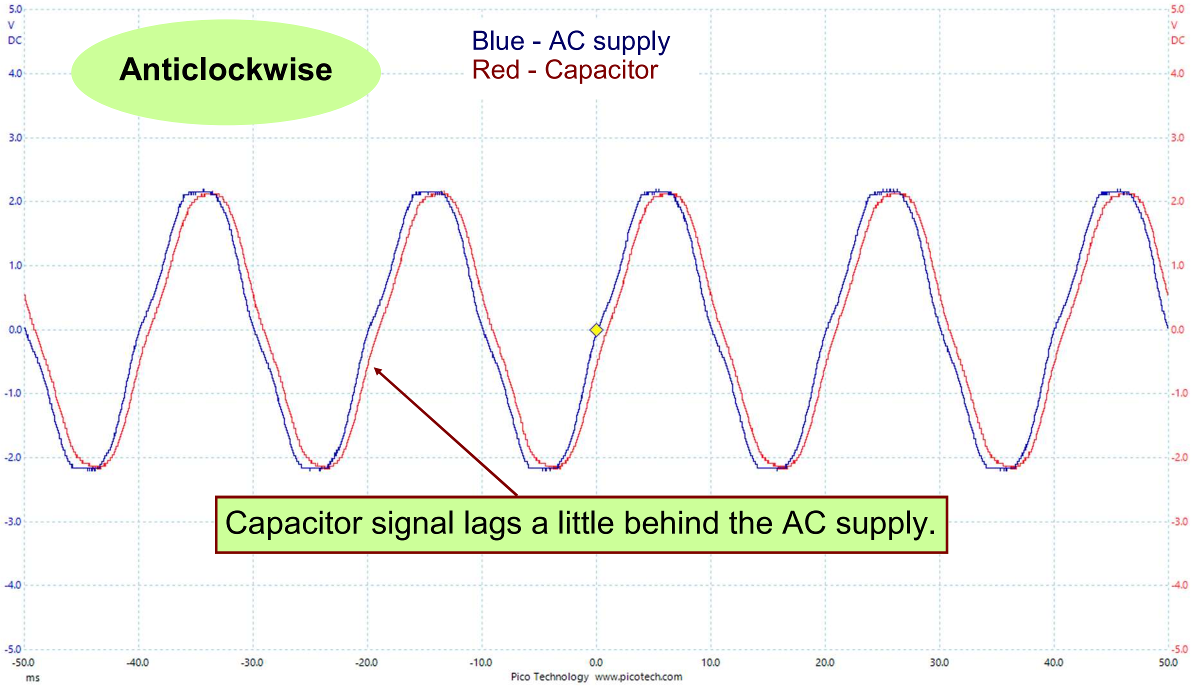
Challenge:

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

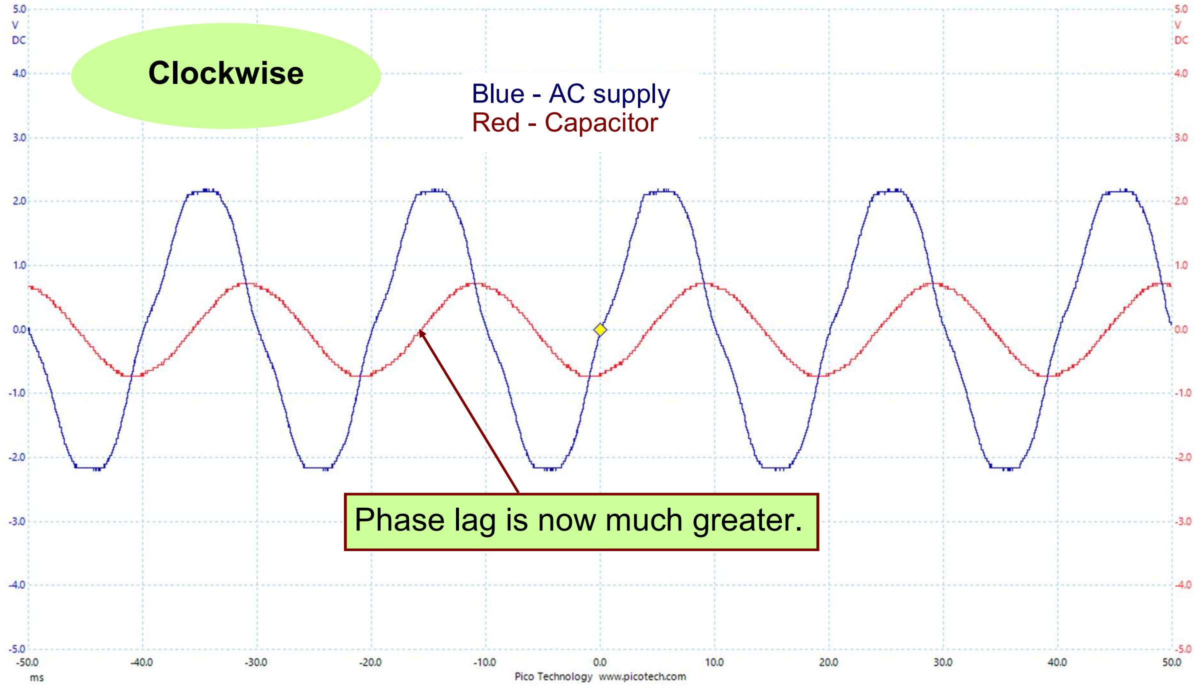
So what?

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.



Capacitor signal lags a little behind the AC supply.



Phase lag is now much greater.

Worksheet 12
Lamp control - thyristor

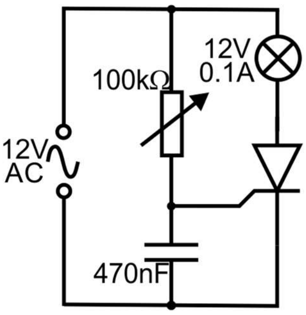
The thyristor and its relative, the triac, are used in a wide variety of lamp dimmer circuits, in the home, in theatres and in public buildings such as sports stadia.

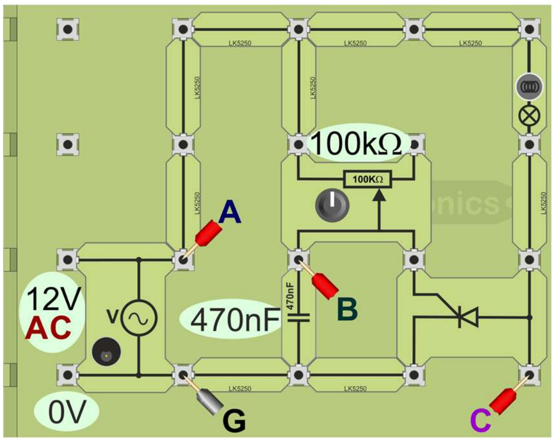
This worksheet demonstrates how to control the thyristor using ‘phase control’.

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 anti-clockwise.





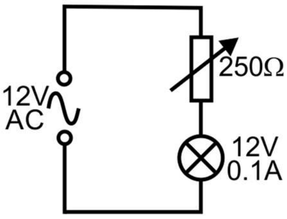
Suitable Picoscope settings:	
Input range: A, B and C	+/-20V DC
Collection time	10ms / div
Trigger mode	Auto
All other settings	Default values

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 .



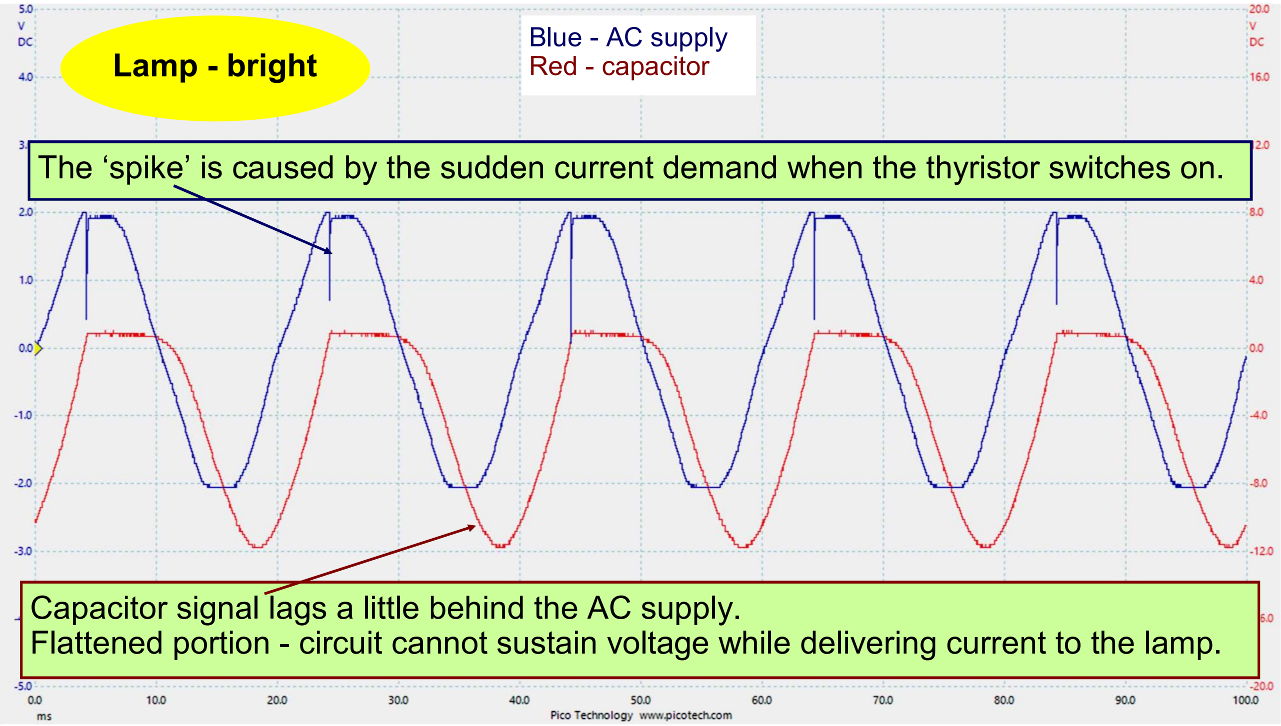
Worksheet 12

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.

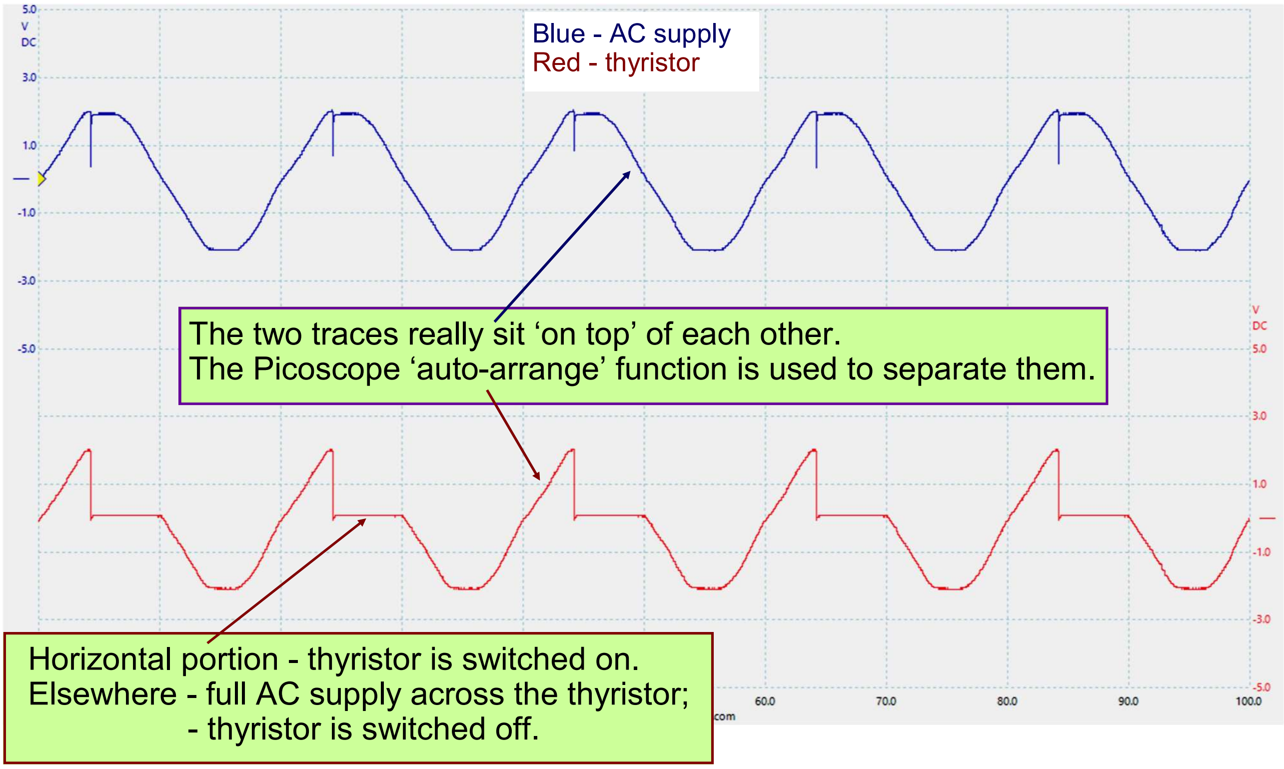


Lamp - bright

Blue - AC supply
Red - capacitor

The ‘spike’ is caused by the sudden current demand when the thyristor switches on.

Capacitor signal lags a little behind the AC supply.
Flattened portion - circuit cannot sustain voltage while delivering current to the lamp.



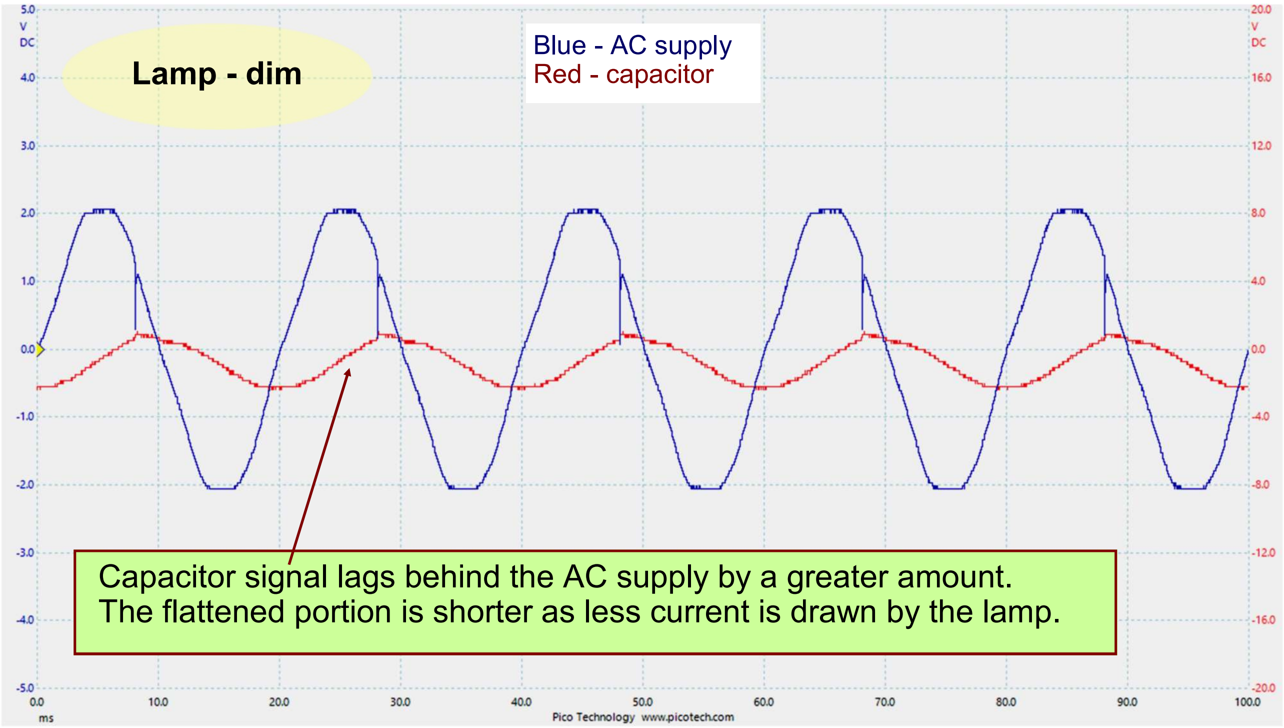
Blue - AC supply
Red - thyristor

The two traces really sit ‘on top’ of each other.
The Picoscope ‘auto-arrange’ function is used to separate them.

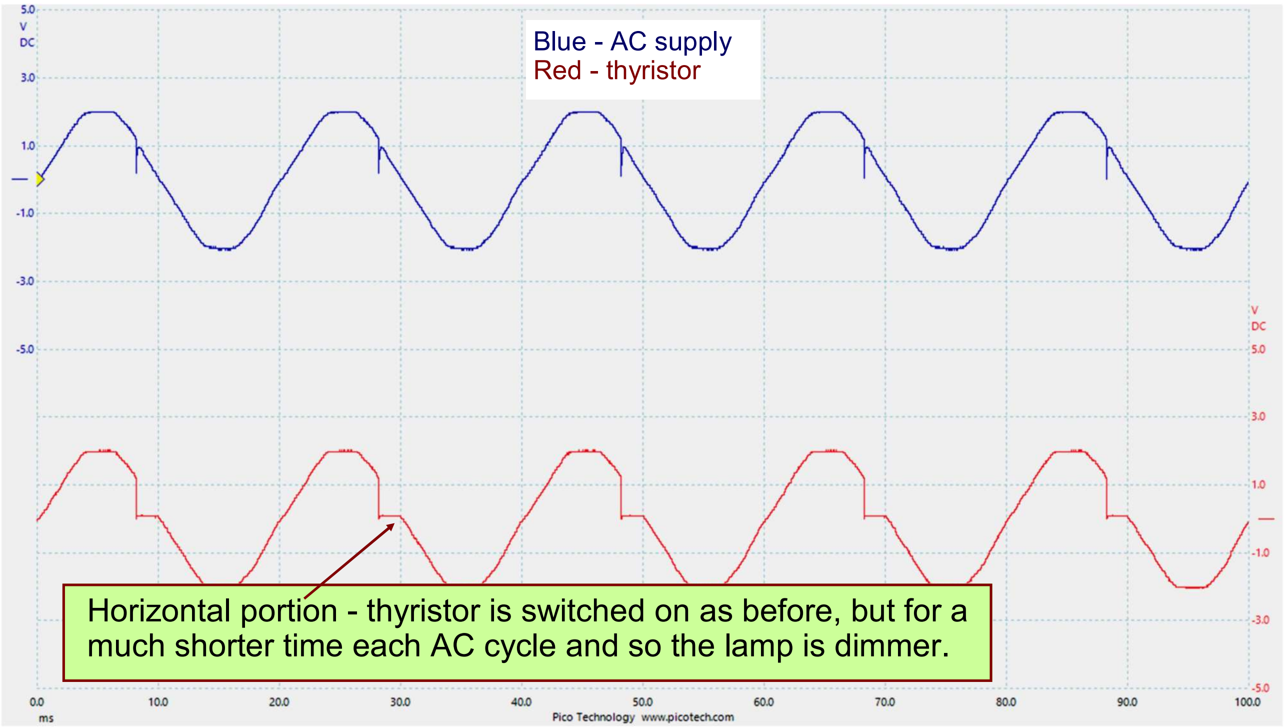
Horizontal portion - thyristor is switched on.
Elsewhere - full AC supply across the thyristor;
- thyristor is switched off.

So what?

Interpreting the traces - continued...:



Capacitor signal lags behind the AC supply by a greater amount.
The flattened portion is shorter as less current is drawn by the lamp.



Horizontal portion - thyristor is switched on as before, but for a much shorter time each AC cycle and so the lamp is dimmer.

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.

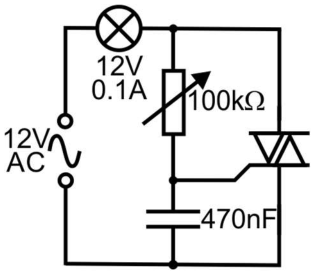
The triac allows current flow in both directions and so delivers more power to the load.

Over to you:

- Build the circuit shown opposite.

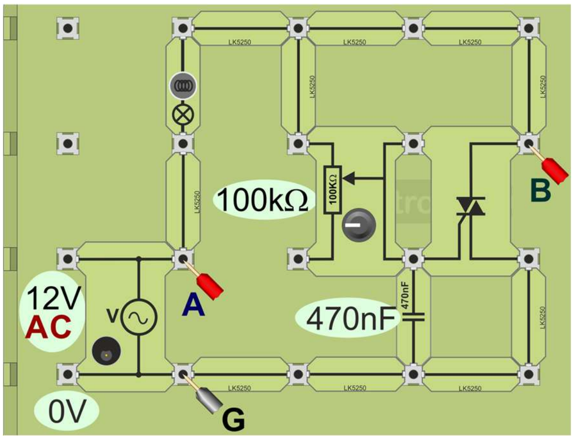
  Look at the equivalent thyristor circuit (worksheet 10). There, the load, (the lamp,) is connected after the phase control network (the resistor and capacitor). Here, it is before them. For most loads, it makes no difference which configuration is chosen.

  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 and B	+/-20V DC
Collection time	10ms / div
Trigger mode	Auto
All other settings	Default



- 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 anti-clockwise.

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.

Worksheet 13

Lamp control - triac

So what?

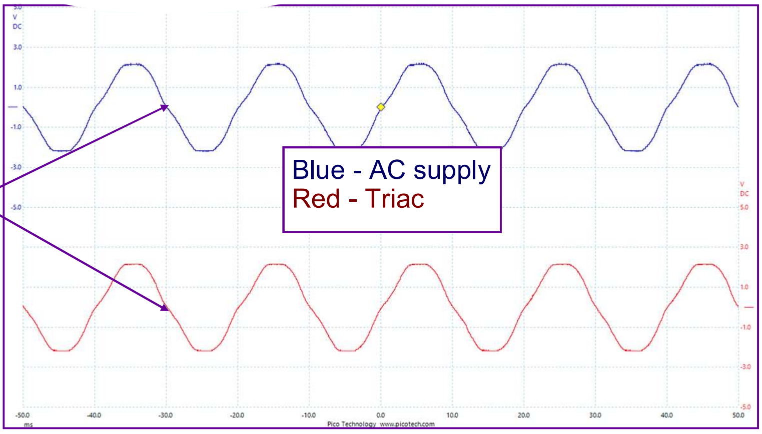
You probably noticed a sudden change in the brightness of the lamp as you adjusted the ‘pot’. The cause can be seen in the sample Picoscope traces shown below.

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.

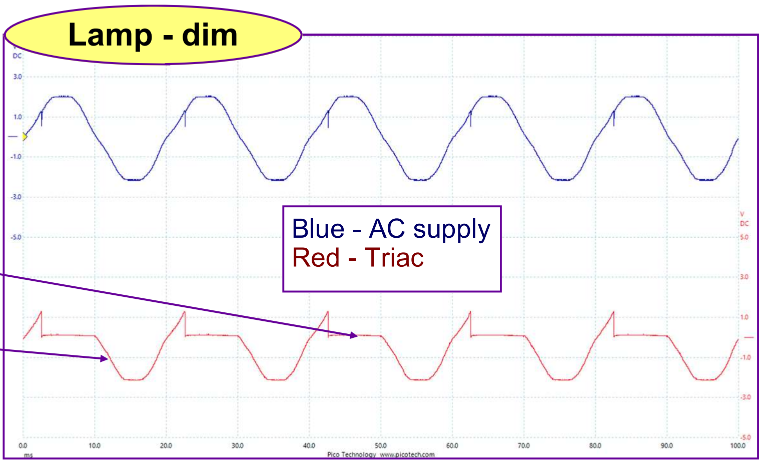
Lamp - off

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



Lamp - dim

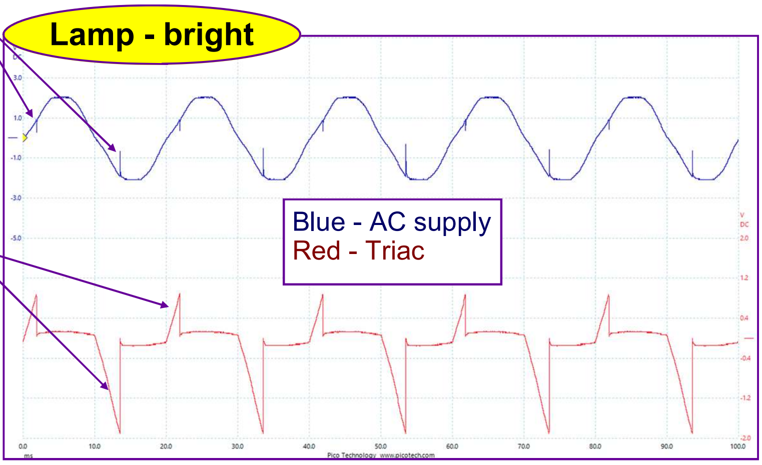
The triac switches on for part of the positive half-cycle (shown by the horizontal part of the trace) but is off throughout the negative half-cycle.



Lamp - bright

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.



Worksheet 14
The UJT relaxation oscillator

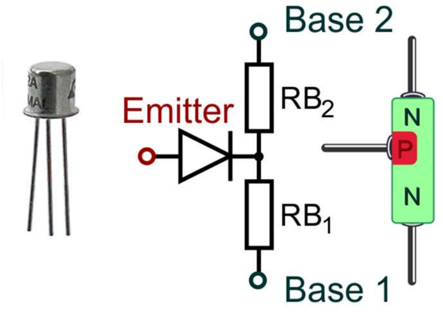
The UJT (unijunction transistor) has only one p-n junction, as its name suggests. However, it has three terminals, two called bases - base 1 and base 2, and one emitter.

It has one aim in life - to oscillate.

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

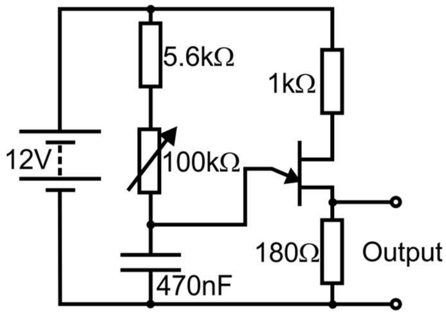
The diagram has details of the device. Its appearance is very similar to other, bipolar, transistors.

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.

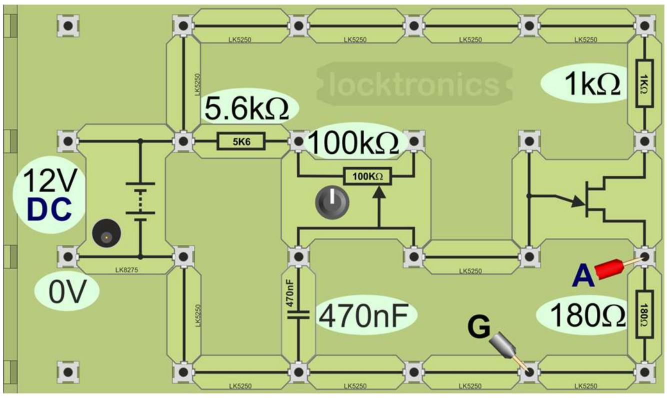


Over to you:

- 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.)

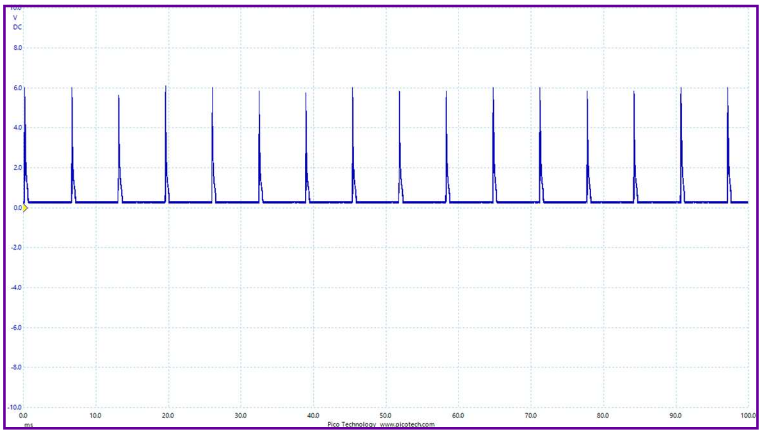
Worksheet 14
The UJT relaxation oscillator

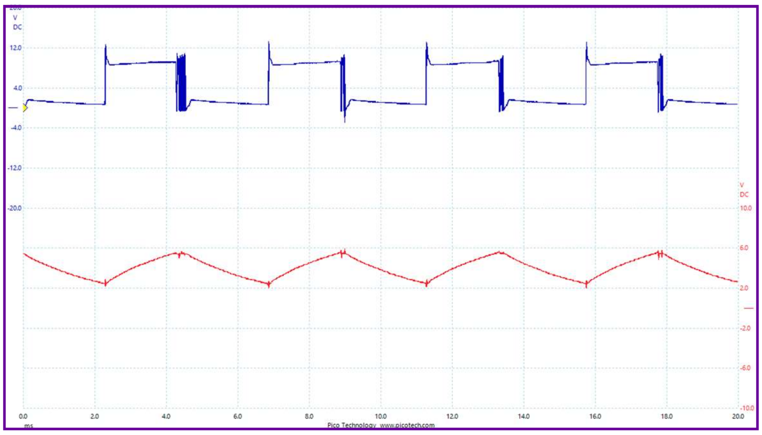
So what:

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?

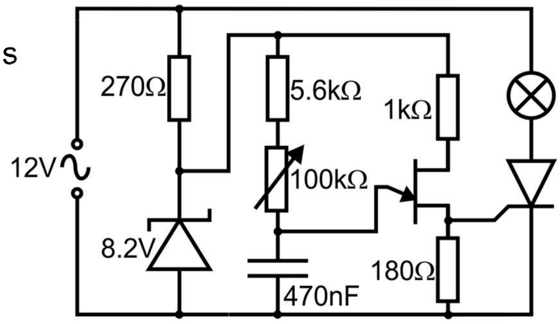
Worksheet 15

Lamp control - UJT and thyristor

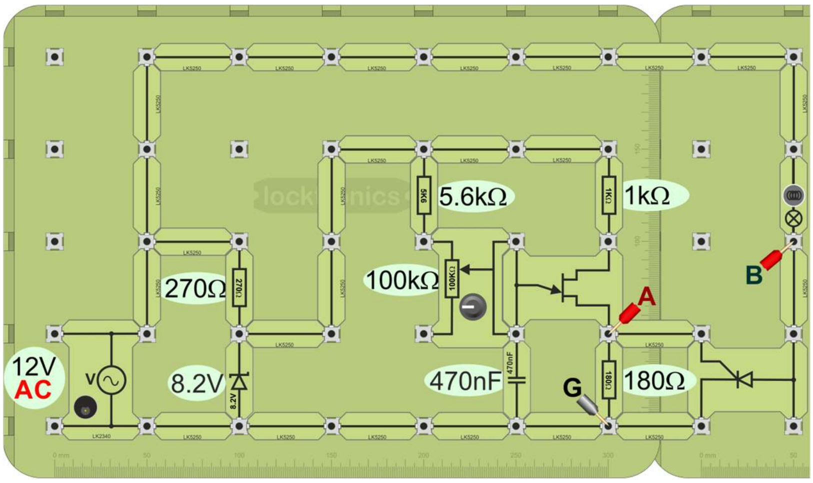
The thyristor is designed to switch huge currents and voltages, hundreds of amps, thousands of volts, in devices like the motors that roll steel in steel mills. To do so, they must switch on and off extremely rapidly. To linger in between these states would dissipate so much energy in the thyristor that 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 B	+/-20V DC
Collection time	10ms / div
Trigger mode	Auto
All other settings	Default

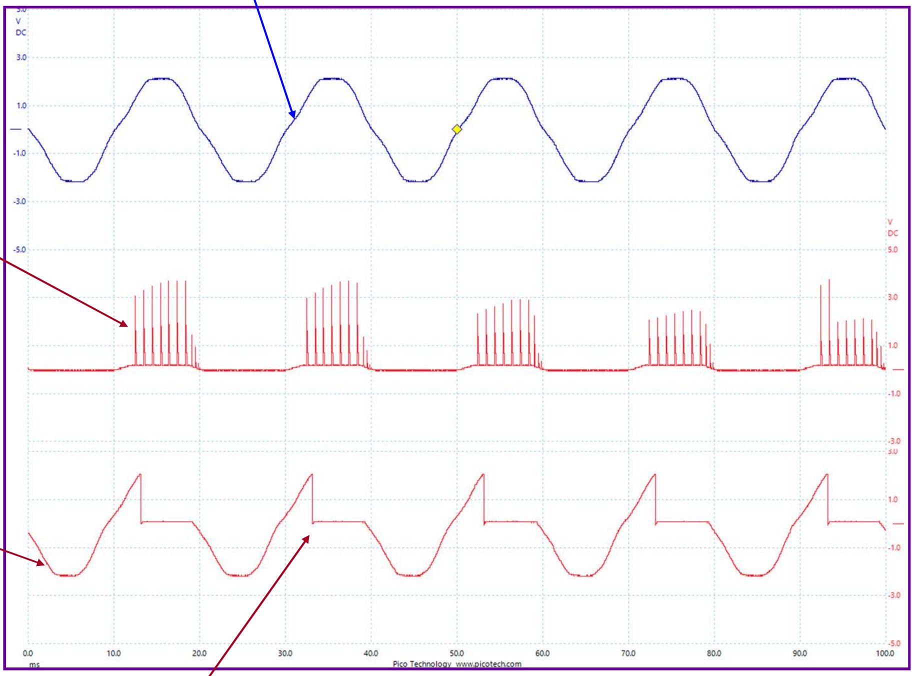
- Adjust the 'pot'.
- Notice the effect on the brightness of the lamp.
- Select two settings for the variable resistor, one giving a bright light and the other dim, and save or print the resulting Picoscope traces for your records.
- Answer the questions raised in the Student Handbook.

Worksheet 15

Lamp control - UJT and thyristor

So what:

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



The AC supply voltage

The UJT oscillations:
These occur only during the 'positive' half-cycle of the AC supply, as that is when the zener diode provides a positive DC voltage.
The frequency of the 'spikes' depends on the setting of the variable resistor .

The thyristor signal:
During the 'negative' half-cycle of the AC supply, the thyristor is switched off and the full AC voltage appears across it.

The thyristor signal:
During the 'positive' half-cycle, the thyristor is switched off until the gate receives first 'spike' from the UJT. It then switches on - the horizontal section of the trace - and the AC supply voltage appears across the lamp. Within the 'positive' half-cycle, the earlier the 'spike' arrives, the sooner the thyristor switches on and the brighter the lamp.

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 ~8.2 / 7k i.e. ~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.

Worksheet 16

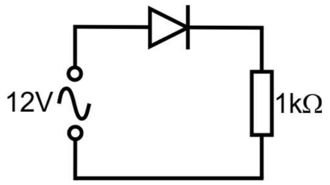
Voltage conversion - half-wave rectification

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

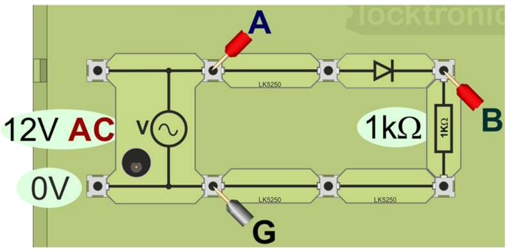
Rectification is the process of turning AC into DC. The diode is the device used to make this conversion. There are several ways in which it can be used to do this.
This worksheet looks at the simplest - the half-wave rectifier.

Over to you:

- Build the circuit shown opposite. The 1kΩ 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 1kΩ resistor, (connections **B** and **G**);



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

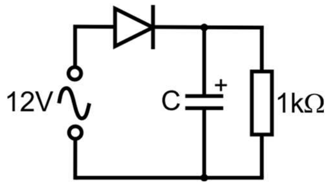


- Save the traces for your records, or print them out .

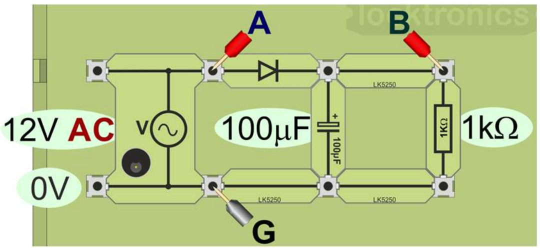
The performance is improved by adding a capacitor, known as a 'smoothing' or 'reservoir' capacitor. Its effectiveness depends on its size and on the current drawn from the rectifier.

- Modify the circuit by adding capacitor '**C**' as shown in the second diagram. To begin with, use a 100µF capacitor.

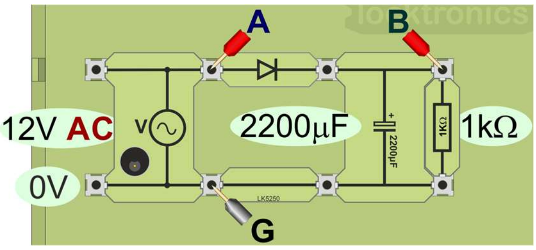
  Take care to connect the capacitor the right way round, as shown in the diagram!



- With the same Picoscope settings as before, record the signal across the AC supply and 1kΩ load and save it for your records.



- Now swap the capacitor for a bigger value, 2200µF, as shown in the bottom diagram.
- Record the new signals across the AC supply and 1kΩ load and save it for your records.
- Answer the questions in the Student Handbook.



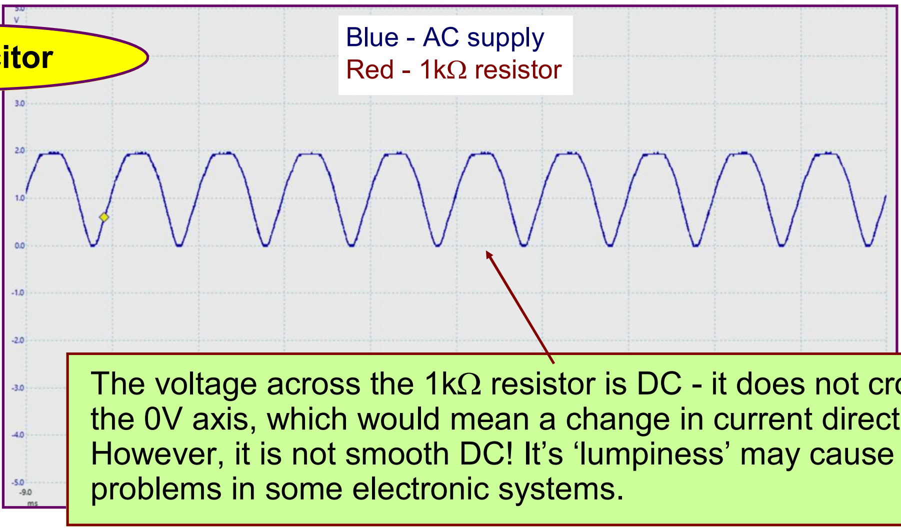
Worksheet 16

Voltage conversion - half-wave rectification

So what:

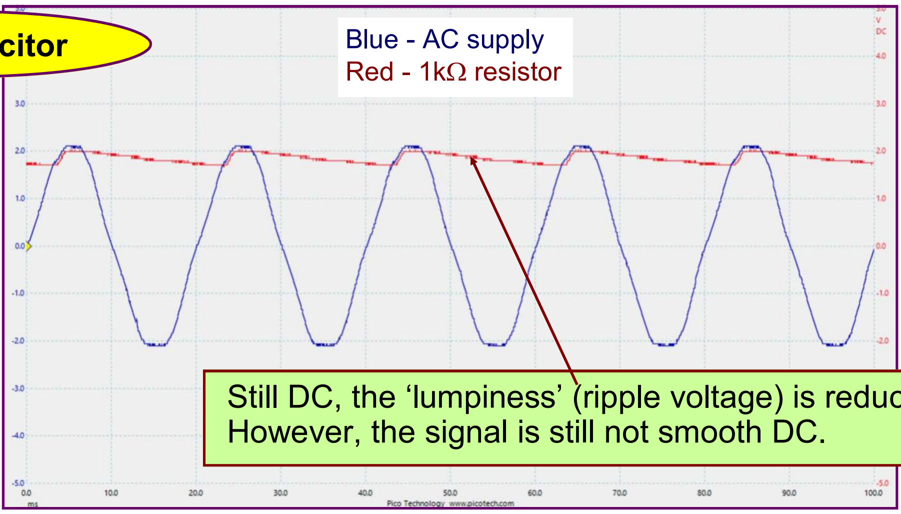
The following are typical traces from this investigation.The signal amplitude appears to be around 2.0V because the ‘X10’ switches on the probes were used, for clarity.
The actual amplitude was slightly greater than 20V.

No capacitor



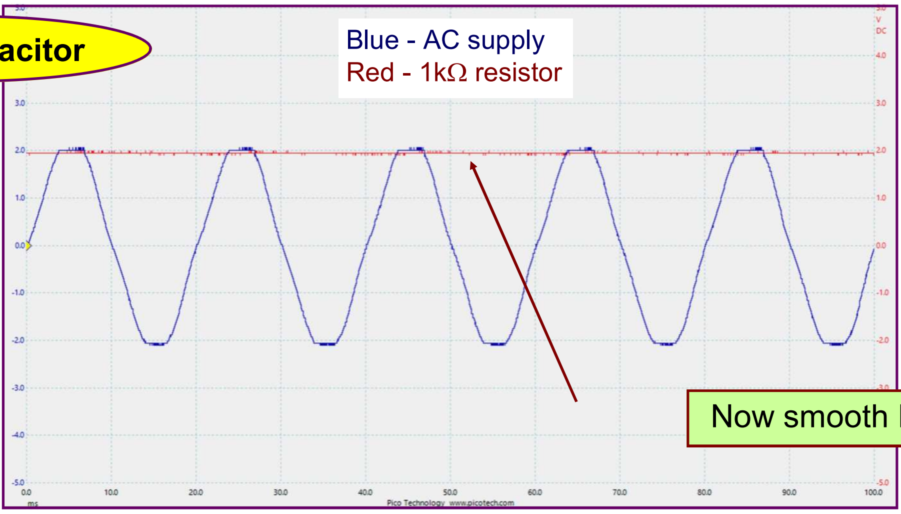
The voltage across the 1kΩ resistor is DC - it does not cross the 0V axis, which would mean a change in current direction. However, it is not smooth DC! It’s ‘lumpiness’ may cause problems in some electronic systems.

100μF capacitor



Still DC, the ‘lumpiness’ (ripple voltage) is reduced. However, the signal is still not smooth DC.

2200μF capacitor

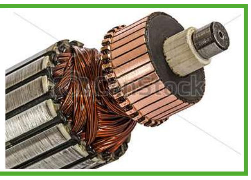


Now smooth DC!

Worksheet 17

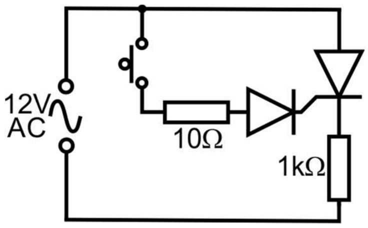
Controlled half-wave rectification

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.

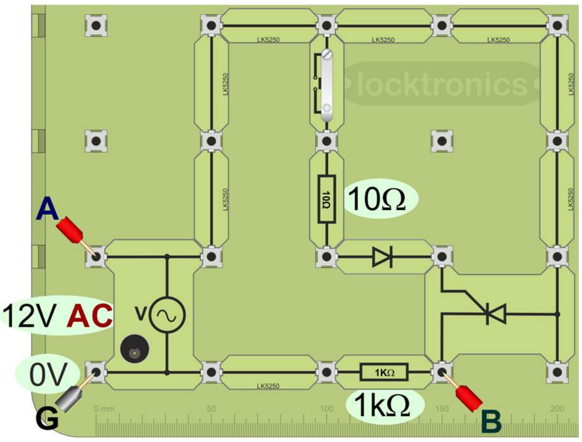


Over to you:

- Build the circuit shown opposite.
  The 1kΩ 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 1kΩ resistor, (connections **B** and **G**).

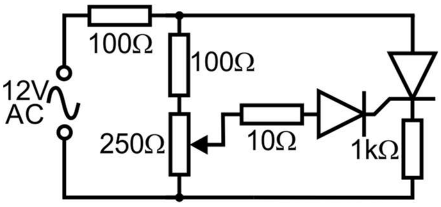


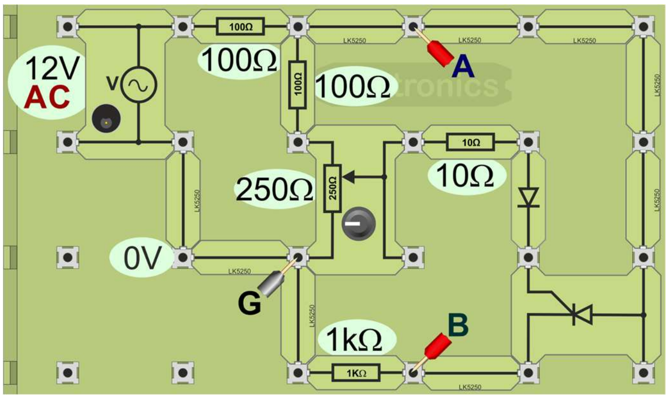
Suitable Picoscope settings:	
Input range: A and B	+/-20V DC
Collection time	10ms / div
Trigger mode	Auto
All other settings	Default



- 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.)



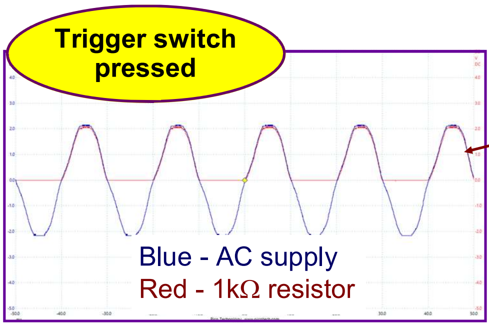


- Notice the effect of adjusting the 'pot'.
- Use Picoscope, with the same settings, to record the signals across the modified supply (at **A**,) and across the1kΩ load (at **B**,) for two different settings of the 'pot'.
- Save or print them for your records.
- Answer the questions in the Student Handbook.

Worksheet 17
Controlled half-wave rectification

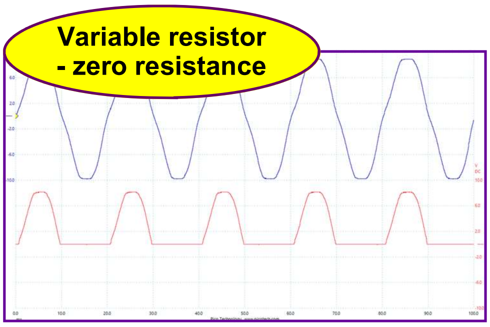
So what:

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

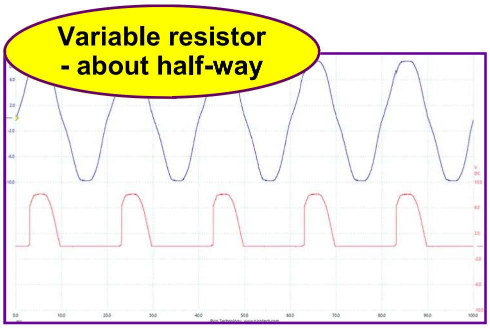


As before, the voltage across the 1kΩ resistor is DC It does not cross the 0V axis. As soon as the thyristor is forward biased, it begins to conduct and continues to do so until the supply voltage reverses.

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.



Blue - AC supply
Red - 1kΩ resistor

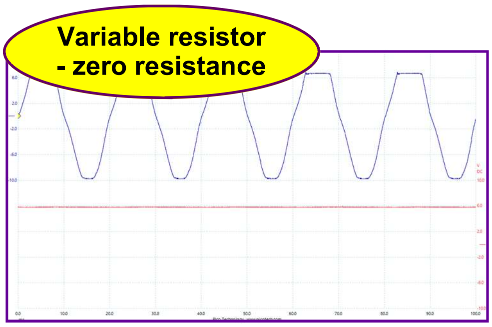


The thyristor conducts almost immediately each half-cycle. The effect is the same as in simple half-wave rectification.

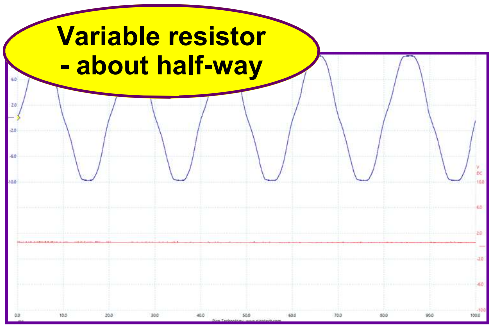
Conduction is delayed each half-cycle. The average output voltage is reduced.

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.



Blue - AC supply
Red - 1kΩ resistor



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

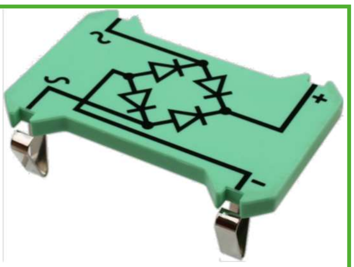
The result of smoothing is again DC, but lower in voltage, around 0.5V.

Worksheet 18

Voltage conversion - full-wave rectification

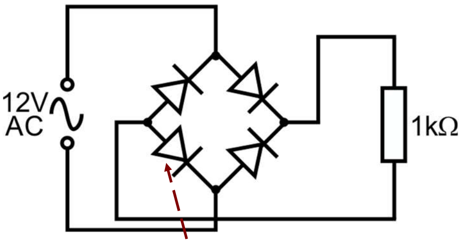
A half-wave rectifier circuit uses only one diode, but it does not make efficient use of the electrical energy on offer. For half of the time, no current at all flows through the load.

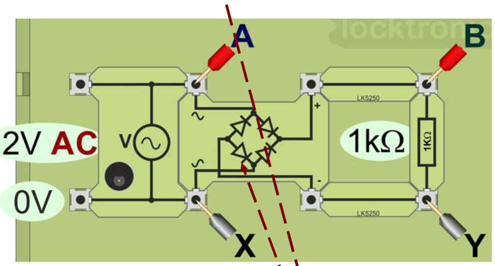
A full-wave rectifier overcomes this limitation, but uses a number of diodes to do so, and so drops more of the AC voltage across them.



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 and B	+/-20V DC
Collection time	10ms / div
Trigger mode	Auto
All other settings	Default

- 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 .

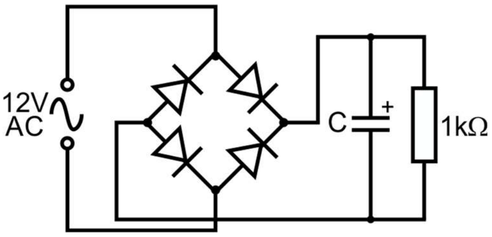
Important!
If the oscilloscope has two input channels, DO NOT attempt to monitor both signals at the same time!
This will short-circuit a diode. (This one!)

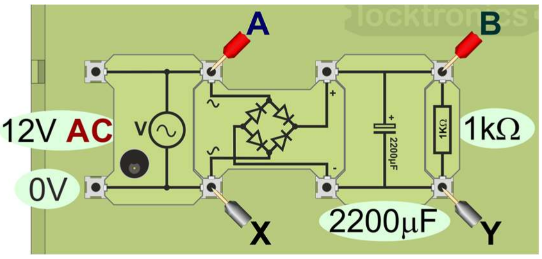
The DC output is steadier than that for half-wave rectification, but still varies. The remedy is the same as in the last investigation - a large capacitor connected across the rectifier output.

- 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.





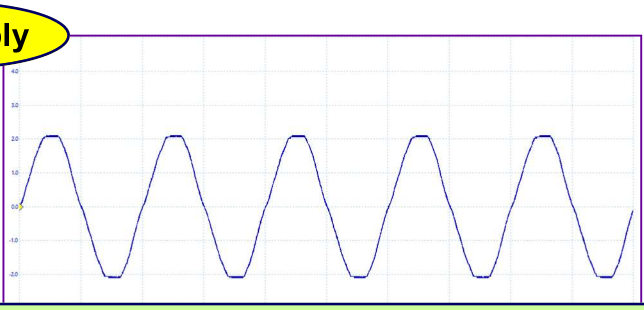
Worksheet 18

Voltage conversion - full-wave rectification

So what:

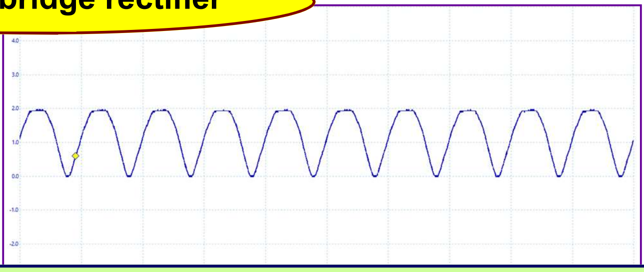
The following traces were obtained from the investigation.

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

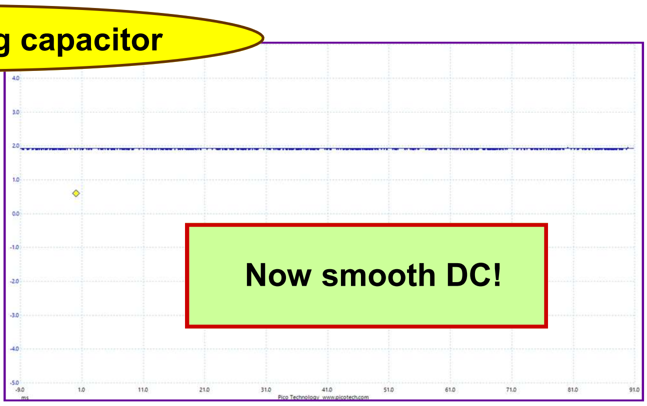


The voltage is DC throughout - it does not cross the 0V axis. However, it is not smooth DC!

100μF 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.

2200μF smoothing capacitor



Now smooth DC!

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 supply 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.

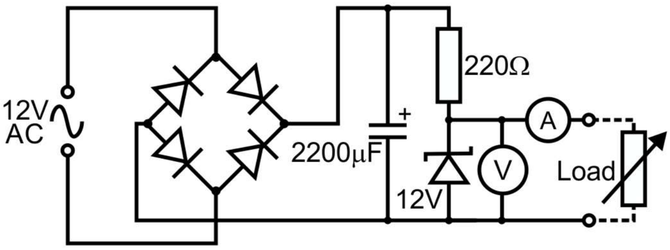
The zener diode is at the heart of most voltage regulators because of its ability to deliver a range of currents with little change in the voltage across it.

Over to you:

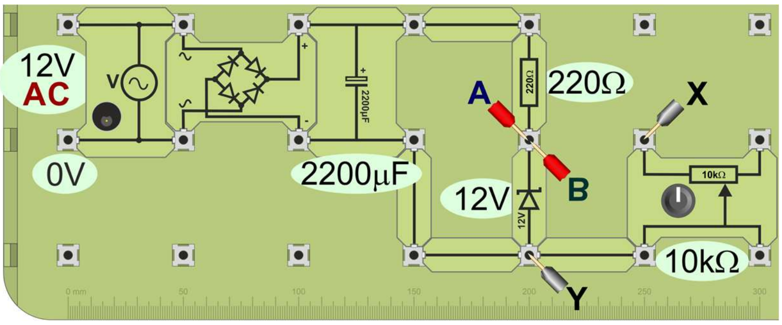
In the circuit that follows, the full-wave rectifier converts the AC supply to DC. It is followed by a zener diode voltage regulator, the focus of the investigation, which supplies current to a variable resistor, representing the load connected to the power supply. Adjusting it changes the output current 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, $\mathbf{V_{OUT}}$, with no output current ($\mathbf{I_{LOAD}}$, = 0mA).
- Connect an ammeter, set to read DC currents up to 200mA to points **B** and **X**, to monitor the output current, $\mathbf{I_{LOAD}}$, .
- Adjust the 'pot' to give an output current, $\mathbf{I_{LOAD}}$, of 5mA and read the output voltage, $\mathbf{V_{OUT}}$.



- 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 $\mathbf{V_{OUT}}$ against $\mathbf{I_{LOAD}}$ and use it to answer the question in the Student Handbook.

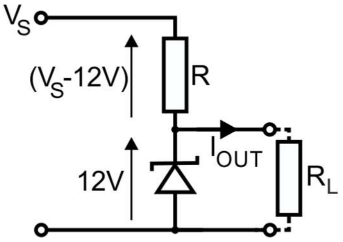
Worksheet 19

Zener diode voltage regulator

So what:

The analysis goes like this:

- The supply has a peak voltage of 12 x √2 = 17.0V.
- Assuming a voltage drop of 2 x 0.7 = 1.4V across the bridge rectifier, gives a DC voltage to the voltage regulator of V_S = 15.6V.
- Voltage across zener diode = 12V, leaving 15.6 - 12 = 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 = 500/12 = 41.7mA.
This is the **maximum** permissible current through resistor R.

Hence, using ‘R = V/I’, **minimum** value of resistor R = 3.6/41.7mA = 86.3Ω.
The investigation used a value of 220Ω.

When 3.6V is dropped across it, current through it = 3.6/220 = 16mA.
This dissipates 16 x 12 = 196mW 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 (from Locktronics Technical Guide).

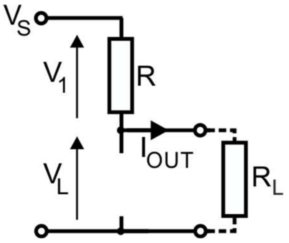
Hence, the maximum permissible output current, I_{OUT}, = 16 - 5 = 11mA.

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:

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



Worksheet 20

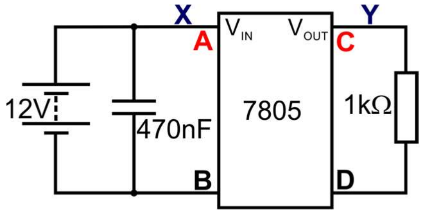
The 7805 voltage regulator

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.

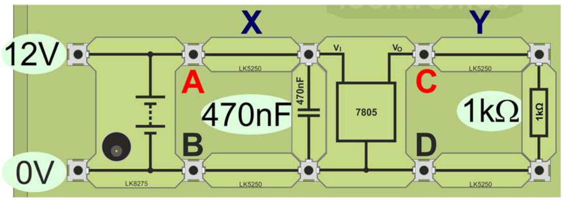
Over to you:

In the following circuits, the 1kΩ resistor represents the circuit supplied by the regulator. The 470nF capacitor filters out high frequency noise in the power supply, to make tt more stable. This is especially important when a switched-mode power supply is used.

1. Power issues:

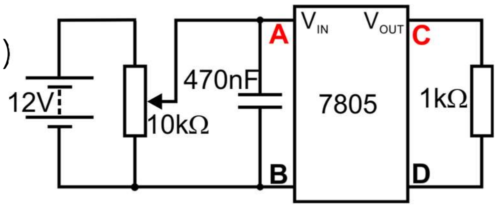


- Build the circuit shown opposite.
- Connect a voltmeter, reading DC voltages up to 20V, to points **A** and **B**, to measure the regulator input voltage, V_{IN}.
- Then connect it to points **C** and **D** to measure the output voltage, V_{OUT}.

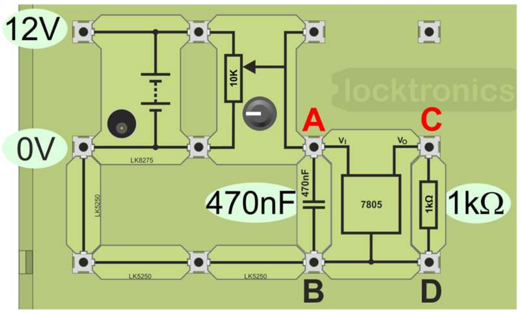


- Remove connecting link **X** and replace it with an ammeter, reading DC currents up to 20mA, to measure the input current, I_{IN}.
- Replace **X**. Next, remove **Y** and in the same way measure the output current, I_{OUT}.
- Record all readings in the Student Handbook and use them to calculate the 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.



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**.

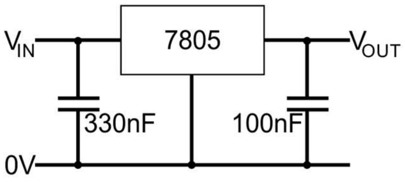
Linear regulators sense changes in output voltage. A feedback loop adjusts the output current to try to return the output voltage to its preset value.

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.



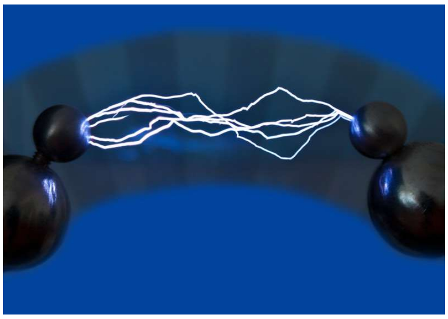
Challenge:

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

The following worksheets study aspects of voltage regulators and power supplies. All are driven by 555 astable subsystems. To speed progress through them, build the astable on one baseboard and keep it. (Occasionally, a component value may change to optimise the frequency for a particular application.) Then add the subsystem under investigation on the second baseboard and attach it as shown.



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.

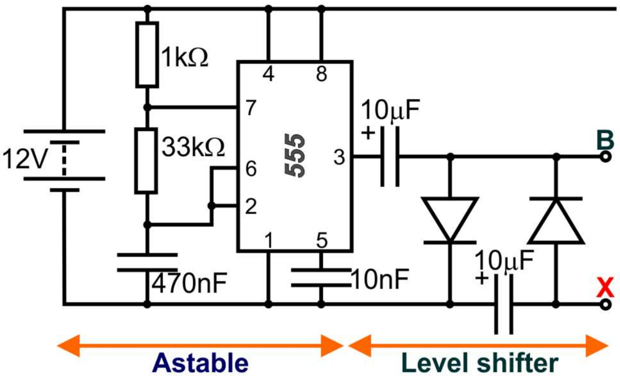
Using only capacitors and diodes, voltage multipliers can step up low voltages to extremely high values and yet be far lighter and cheaper than transformers.

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

Over to you:

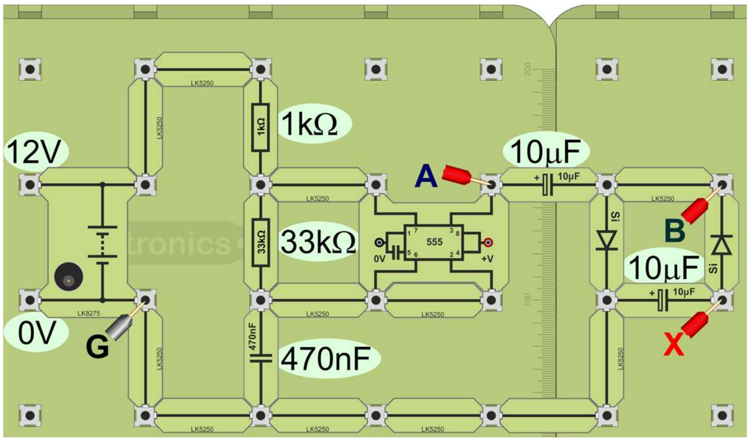
The level shifter circuit consists of two sections:

- an **astable** - turns DC into a pulsing square wave output;
- the **level shifter** - changes the voltage levels of the output.



- 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**).

Suitable Picoscope settings:	
Input range: **A** and **B**	+/-20V DC
Collection time	10ms / div
Trigger mode	Auto
All other settings	Default



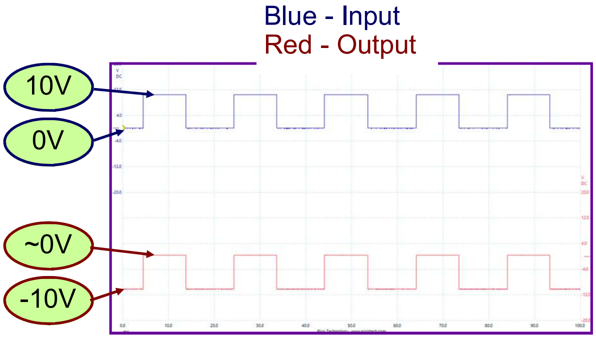
- Then use it to monitor:
  - the astable output, (**A** and **G**);
  - output **X** of the level shifter, (**X** and **G**).
- Save the resulting files, or print them out for your records.

Worksheet 21

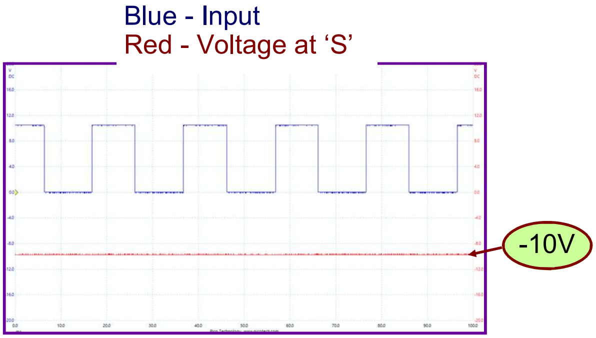
The level shifter

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 output signal is a copy of the input, but at different voltage levels.

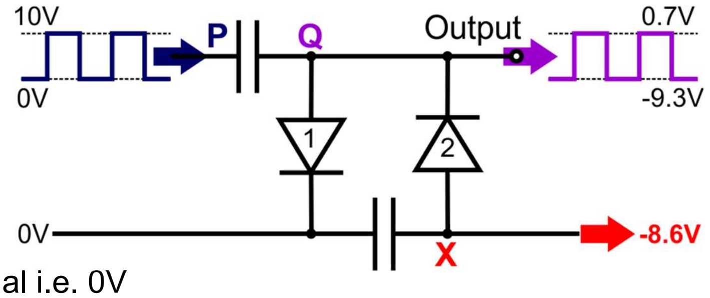


The signal from point ‘X’ is a steady voltage at approximately -10V.

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.

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.

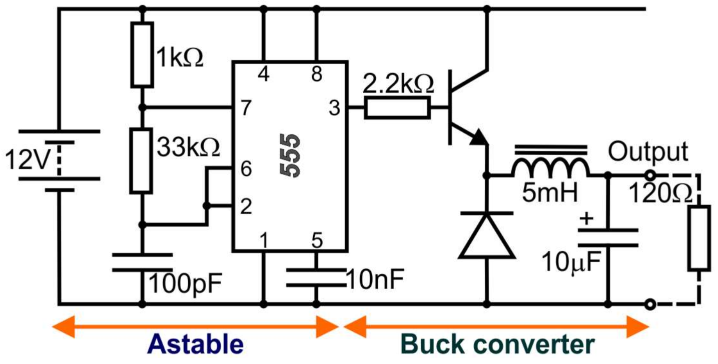
Over to you:

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.

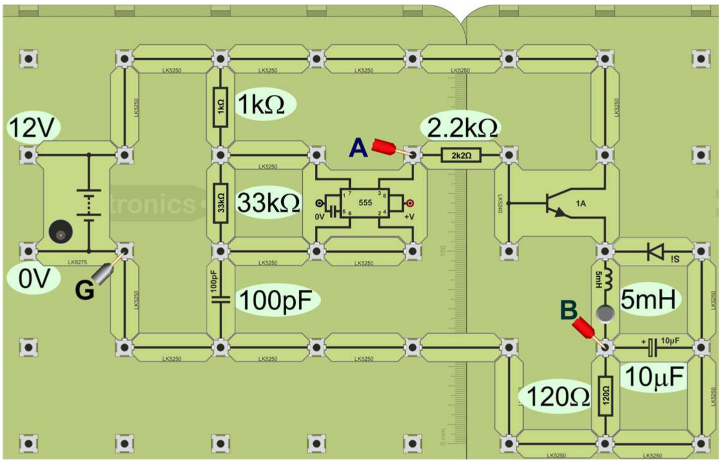
- Build the circuit shown opposite. Once again, for clarity, the power leads to the 555 carrier have been omitted from the layout.

  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, for your records.
- Answer the question posed in the Student Handbook.

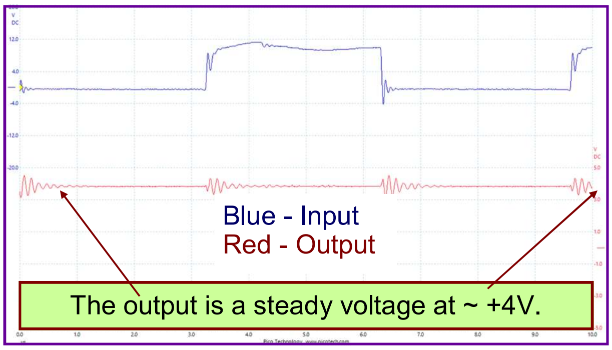
Worksheet 22

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.

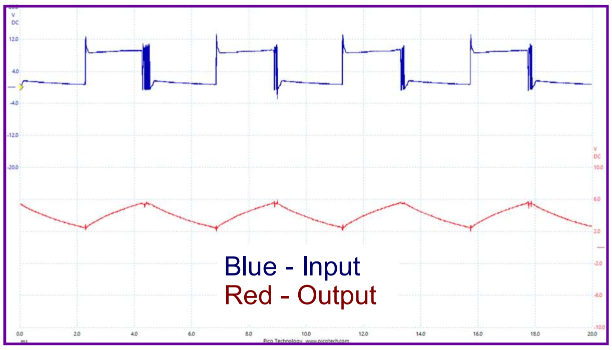


The output is a steady voltage at ~ +4V.

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

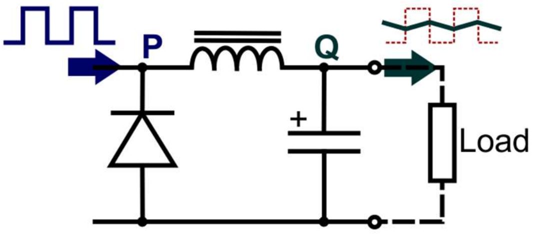
The output is clearly that of a charging and discharging capacitor, changing from around 2.5V to 5.5V.

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.

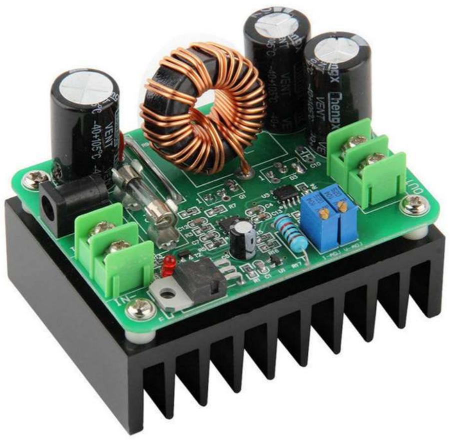
Worksheet 23

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 lighting systems from a single battery.



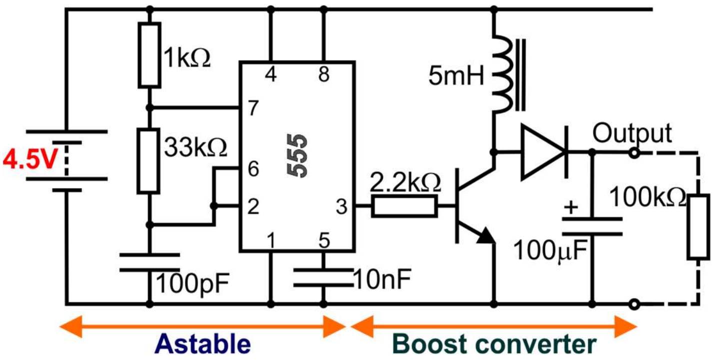
Over to you:

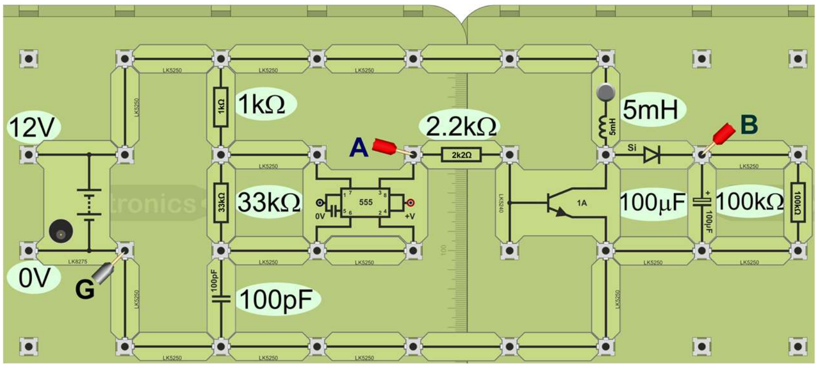
The circuit diagram shows a simple boost converter, again driven from a 555 astable.
The two sections, the astable and the boost converter, have been labelled.
Once again, the transistor acts as a current buffer for the 555 IC. The 100kΩ resistor on the output represents the circuit load.

- 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**).

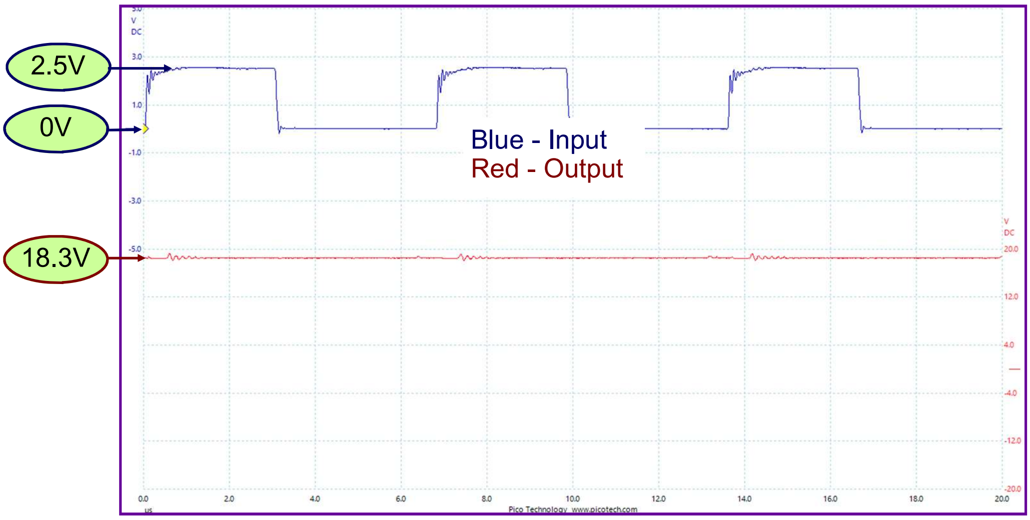
Suitable Picoscope settings:	
Input range: A	+/-5V DC
Input range: B	+/-20V DC
Collection time	2µs / div
Trigger mode	Auto
All other settings	Default

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

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).

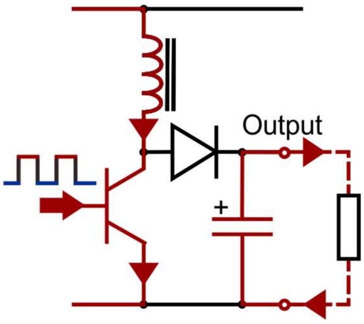
Once again, the output is not well-regulated, but the circuit illustrates the boost converter principle.



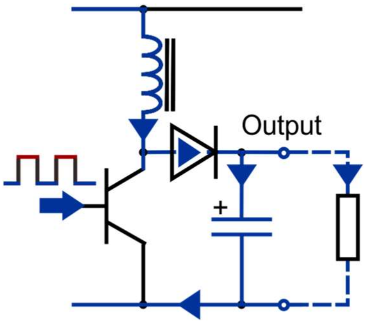
The analysis: (well - one way to look at it!):

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

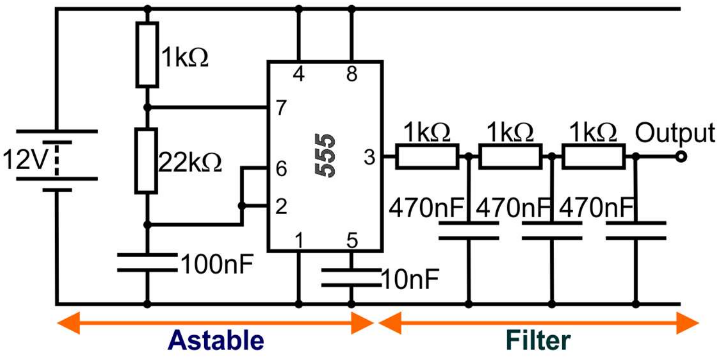
Previous worksheets focused on rectification - AC to DC conversion.

Now the opposite - DC to AC conversion, important 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.

Over to you:

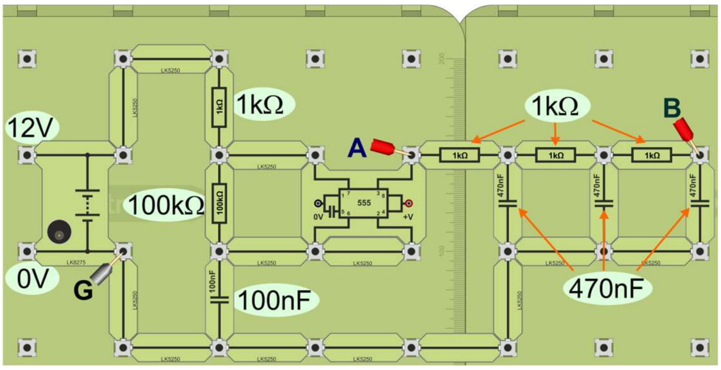
Inverter circuits can be simple or complex, depending on the output required. A basic low power AC power supply, for lighting, for example, can use an inverter as simple as an astable. Its output can be stepped up or down by a transformer to give the voltage needed. At the other extreme, when powering audio equipment, for example, a more sophisticated circuit, involving filters is used to obtain a sinusoidal supply, avoiding audible hum on the equipment.

This inverter circuit consists of two sections:
- an **astable** - turns DC into a pulsing square wave output;
- a simple **filter** - removes most of the high frequency square wave components, leaving an approximately sinusoidal output.



- Build the circuit shown opposite. 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 inverter output, (**B** and **G**).

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



- Save the resulting files, or print them out.

Challenge:

- 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.)

So what:

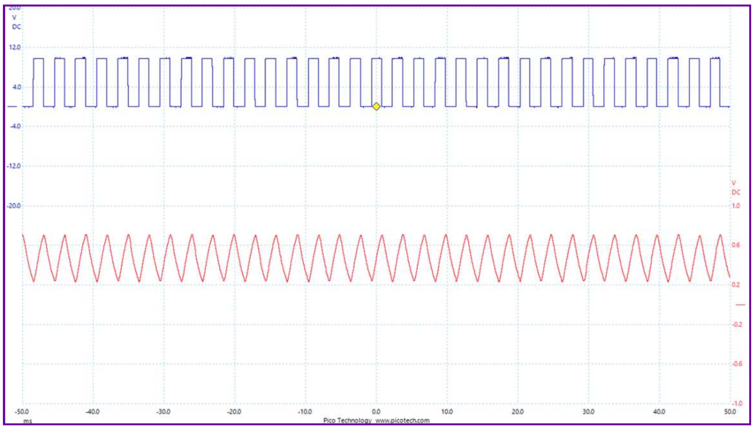
According to Fourier's theorem, a signal like a square wave can be created by combining a series of sine waves of different frequencies and amplitudes. (A sine wave is considered to be the simplest signal, as it contains only one frequency of oscillation.)

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.

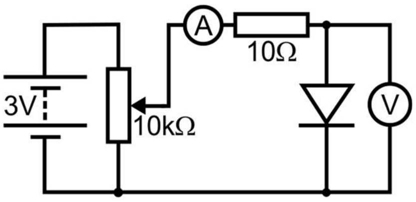


Power
And Energy
Electronics

Student
Handbook

For your records

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, ……………………………………………………………….

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Compared to ideal diode characteristics, ………………..…………………………………...

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Challenge - the LED:

Results for forward bias:

Current in mA	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**	**1.2**	**1.4**	**1.6**	**1.8**	**2.0**
Voltage across LED										

When the LED is reverse-biased, ..……………………………………………………………..

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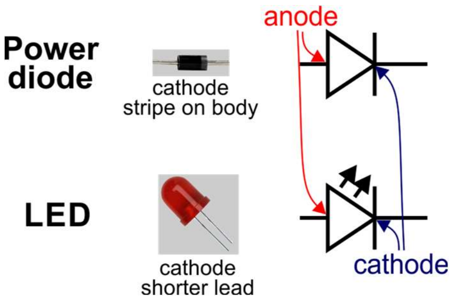
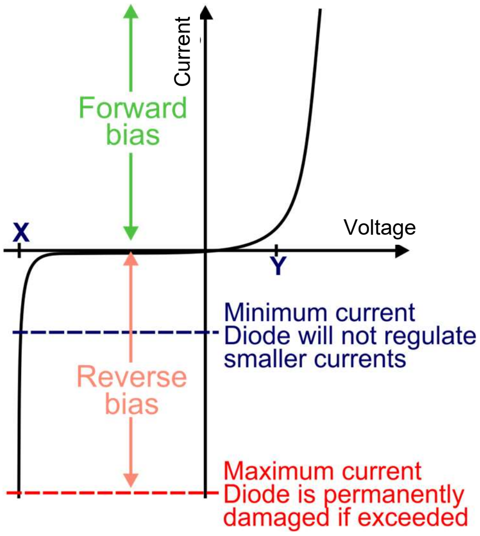
Summary:

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.



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: $I_{max} = P_D / V_Z$.

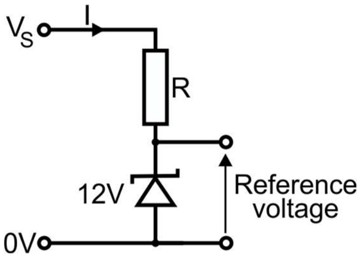
For example, a 1N5913B zener diode has a zener voltage of 3.3V and a steady-state power rating of 1W. This means that it can sustain a reverse current of 1 / 3.3 = 303mA.

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: $V_S = 15V$, $R = 300\Omega$

The voltage across resistor R = $V_S - V_Z$ = 15 - 12 = 3V.

Applying Ohm's law to the resistor,

current I = V / R = 3 / 300 = 0.01A = 10mA.

Power dissipated in the zener diode = V_Z x I = 12 x 10 = 120mW.

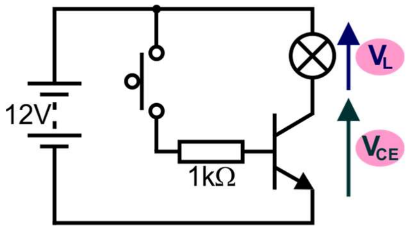
Power dissipated in the resistor = V x I = 3 x 10 = 30mW.

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_{CE}	V_L	Lamp (On / Off)
Open			
Closed			

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

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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.

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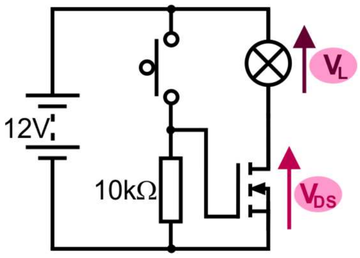
Worksheet 4- On / off control - MOSFET switch

Behaviour of a MOSFET switch



Switch	V_{DS}	V_L
Off		
On		

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

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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.

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

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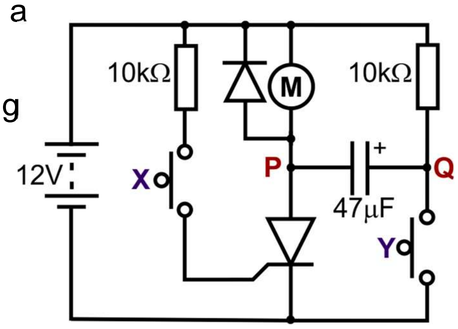
Worksheet 5 - On / off control - thyristor switch

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**?

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Explain why this happens.

…………………………………………………………………………………………………..

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What happens when you press and release switch **Y**?

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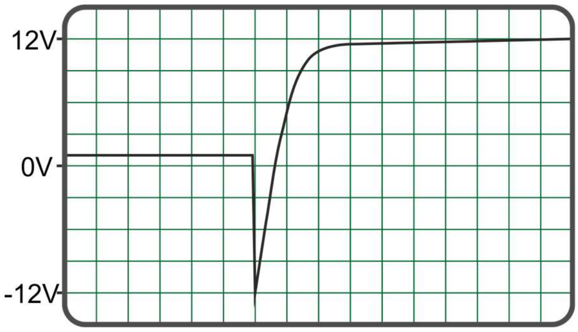
The diagram represents the oscilloscope trace, showing the voltage across the thyristor before and after switch **Y** is pressed and released.

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.

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

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

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Explain the purpose of the flywheel diode in this circuit.

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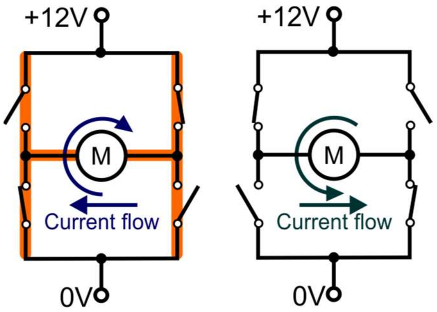
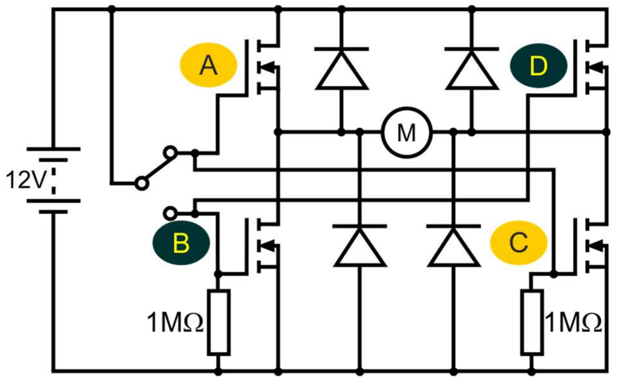
Worksheet 6- On / off / direction control - H-bridge

The principle is illustrated in the diagram below. The name ‘H-bridge’ comes from the ‘H’ configuration, 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:

Changeover switch position	Motor voltage	
	Left-hand side	Right-hand side
Upper		
Mid-way		
Lower		

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

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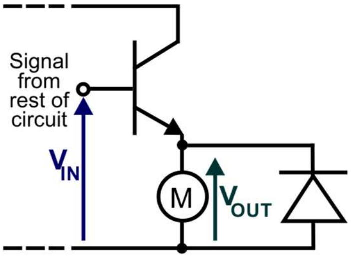
Worksheet 7 - Motor control - BJT emitter follower:

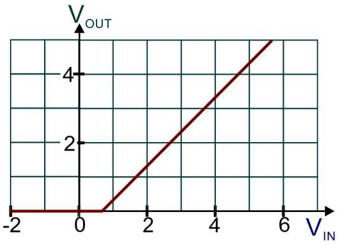


The next step is graduated control where the load device is not simply on or off, but is supplied with a variable voltage, allowing different motor speeds, variable lamp brightness etc.

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}									



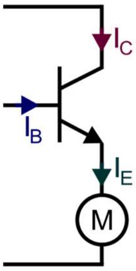
Use your results to plot a graph of **V_{OUT}** against **V_{IN}** (i.e. the voltage transfer characteristics) for the emitter follower.
It should resemble the one shown opposite.

Interpreting the results:

- When the **V_{IN}** is greater than ~0.7V, the transistor starts to conduct.
- As a result, a voltage drop of ~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: $I_E = I_C + I_B$
and $I_C >> I_B$
Hence current gain = ~I_C / I_B = ~ 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).

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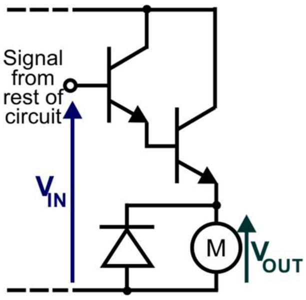
Worksheet 8 - Motor control - darlington driver:

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 $\mathbf{I_{IN}}$ = ………. mA
output current $\mathbf{I_{OUT}}$ = ………. mA

Power gain calculation:

Use your results to complete the following calculations:

Power gain = output power / input power,
where:
input power = $\mathbf{V_{IN}}$ x $\mathbf{I_{IN}}$
= 5 x ……….
= ………. mW;
and output power = $\mathbf{V_{OUT}}$ x $\mathbf{I_{OUT}}$
= …... x …..
= ………. 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:

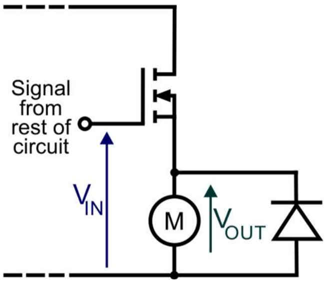
- higher overall voltage drop between input and output (~1.4V compared to ~0.7V for the emitter follower);
- higher saturation voltage, when switched on fully, resulting in higher power dissipation.

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} (~ 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.)

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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?

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Worksheet 10- Motor control - PWM:

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

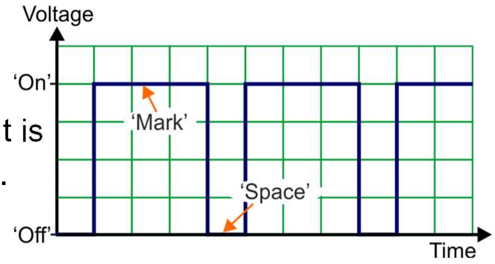
The 'mark' is the time for which it is 'on'.

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.

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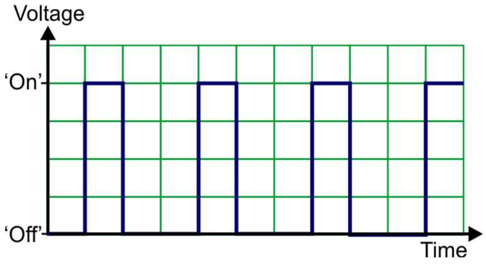

The speed of a motor is controlled by a PWM signal. What happens to the speed when the mark-to-space ratio increases?

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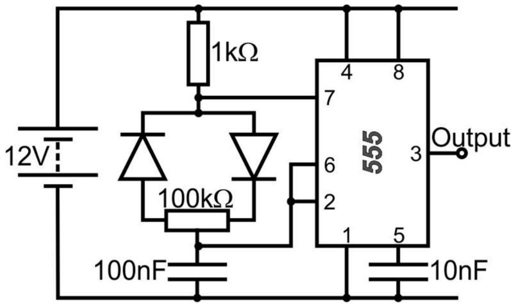
The circuit diagram shows a 555 timer used to generate a PWM signal.



Challenge:

With the 100nF capacitor:

- time period of signal = ………………..
- frequency of signal = ………………..

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

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

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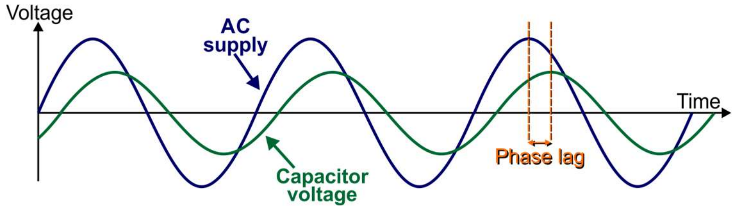
Worksheet 11 - Phase control:

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:

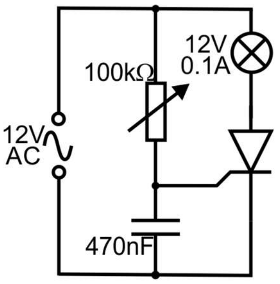
As the knob on the ‘pot’ is rotated clockwise,

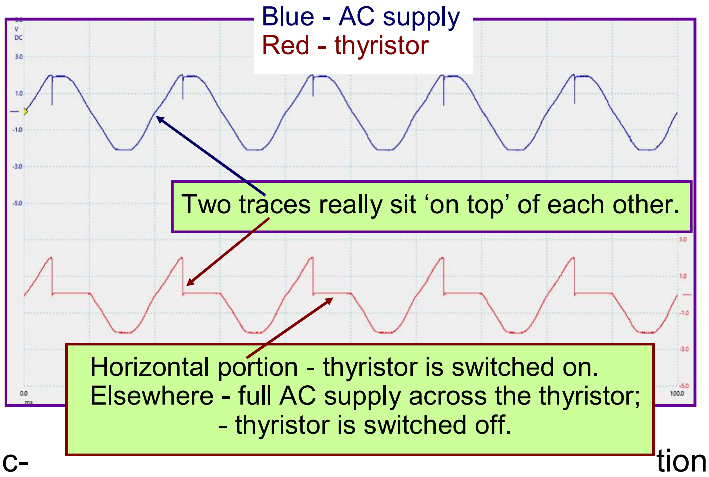
the resistance of the ’pot’ …….…………. and so the phase lag ……..………… .

Increasing the capacitor value ……..………… the phase lag.

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.





Two traces really sit ‘on top’ of each other.

Horizontal portion - thyristor is switched on.
Elsewhere - full AC supply across the thyristor;
- thyristor is switched off.

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.

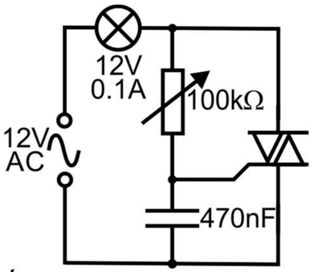
The maximum phase difference between the capacitor signal and the AC supply is 90^0 with this arrangement . What effect will this phase difference have on the brightness of the lamp?

……..

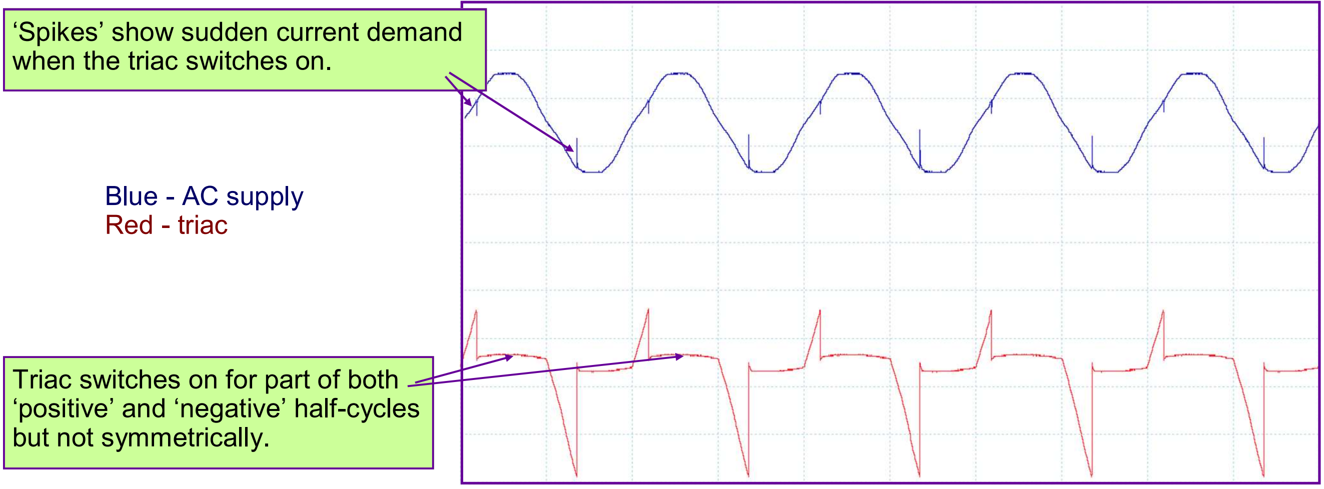
Worksheet 13 - Lamp control - triac:

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.



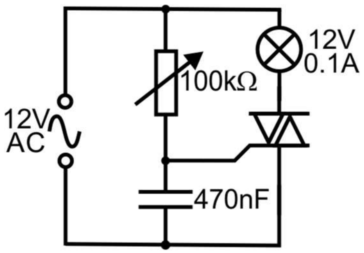
The oscilloscope traces show the voltages across the thyristor and AC supply when the lamp is at nearly full brightness:


‘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?

……………………………………………………………………………

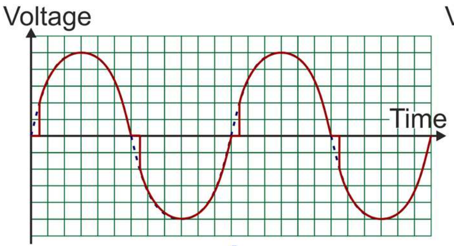
Complete the following:

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

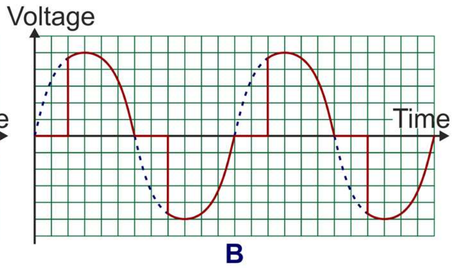
The graphs show two signals across a **lamp** controlled by a triac.

In which is the lamp brighter?

………………

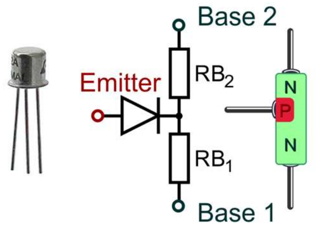


A

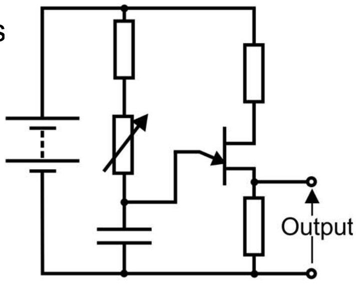


B

Worksheet 14 - The UJT relaxation oscillator



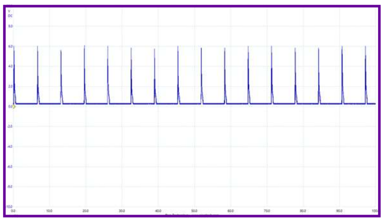
The UJT (unijunction transistor) has only one p-n junction, as its name suggests. However, it has three terminals, two called bases, base 1 and base 2, and one emitter. It consists of a bar of lightly doped n-type silicon, giving it a resistance of a few kilohms, typically. A small p-type area is created 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.

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.

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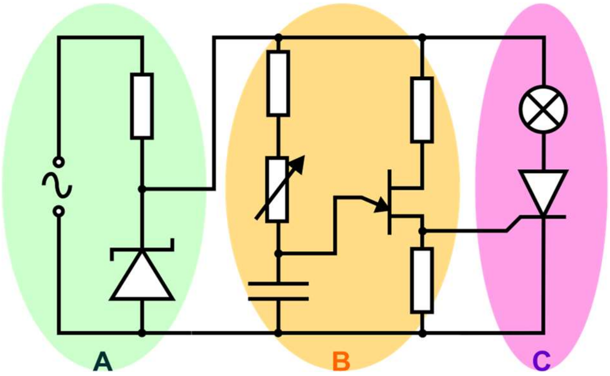
Worksheet 15 - Lamp control - UJT and thyristor

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:

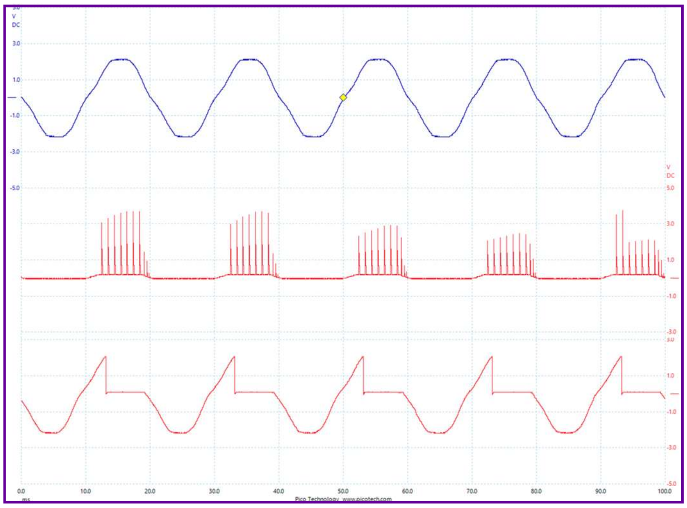
- the UJT oscillator; ………………..
- the zener voltage regulator; ………………..
- the thyristor switch? ……………….. .



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.

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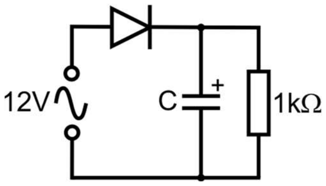
Worksheet 16- Voltage conversion - half-wave rectification:

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.

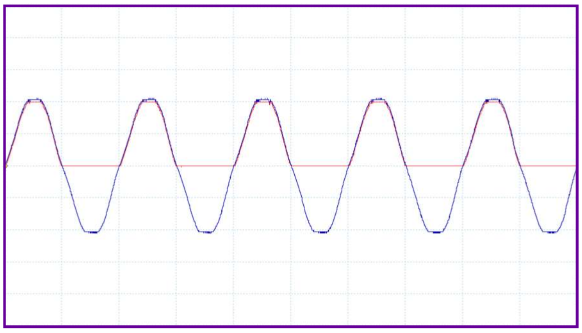
The circuit diagram shows a diode delivering a DC supply to a load, represented by the 1kΩ resistor. The capacitor, known as a reservoir or smoothing capacitor, has the job of 'smoothing' (removing voltage variations,) from the DC supply.



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.

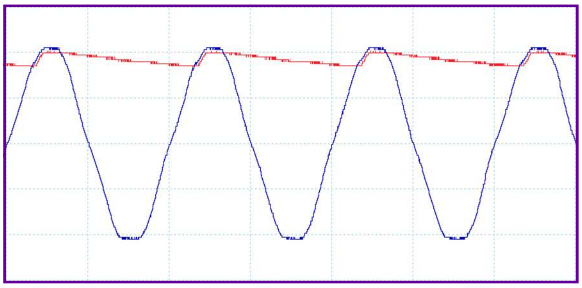


Why do we say that this output is DC?

……………………………………………………………………………………………………..

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?

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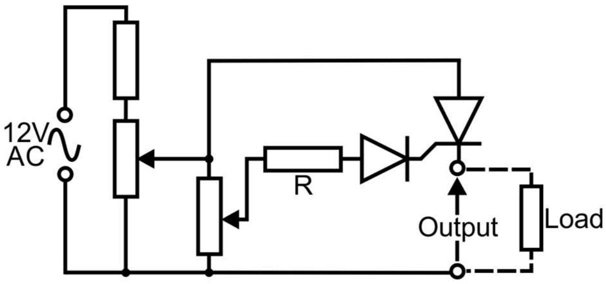
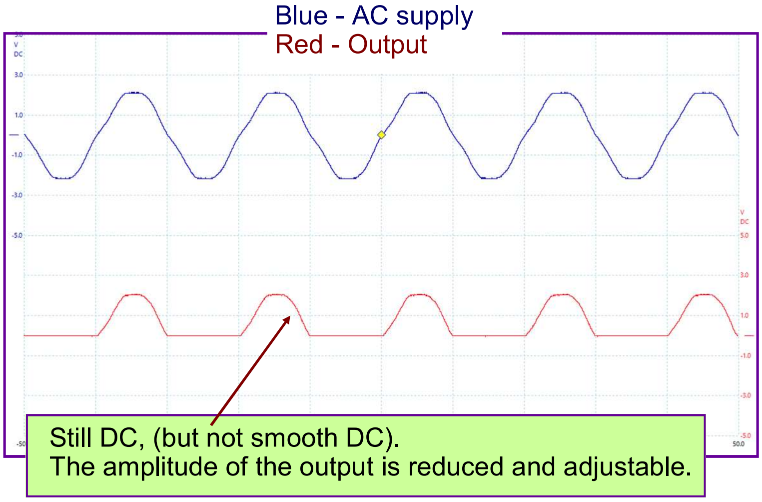
Worksheet 17 - Controlled half-wave rectification:

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.



Still DC, (but not smooth DC).
The amplitude of the output is reduced and adjustable.

Why do we say that this output is DC?

……………………………………………………………………………………………………..

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?

……………………………………………………………………………………………………..

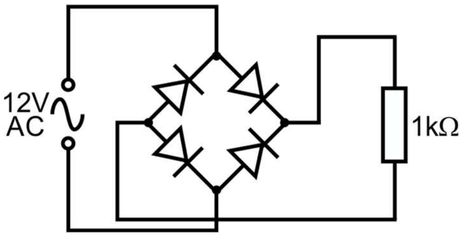
Worksheet 18- Voltage conversion full-wave rectification:

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.

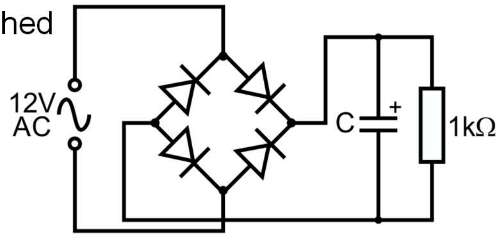
The diagram shows a full-wave rectifier using four diodes.

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.

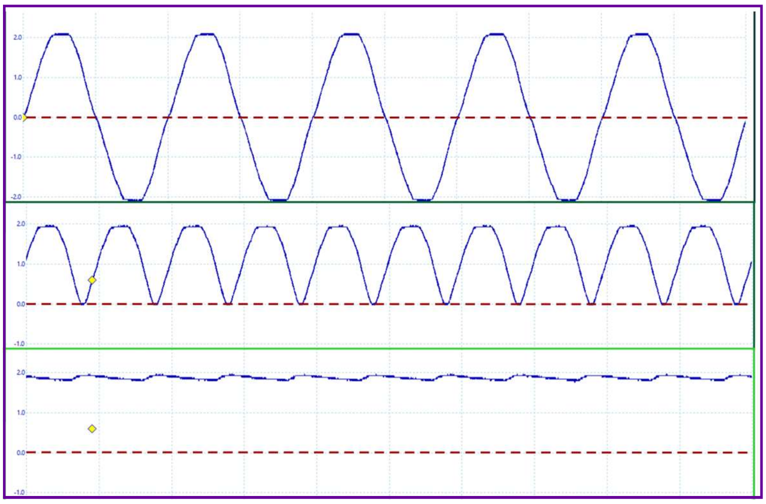


As with half-wave rectification, the DC output can be smoothed by adding a capacitor in parallel with the load.



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:

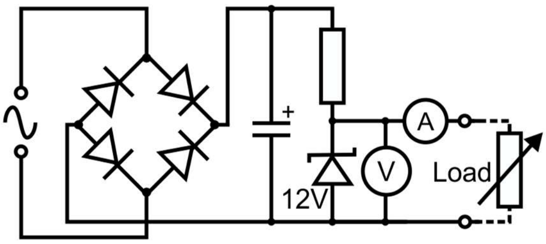
- is DC;
- has twice the frequency of the half-wave waveform.

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:

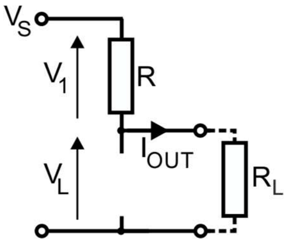
- The supply has a peak voltage of 12 x √2 = 17.0V.
- Voltage drop across the bridge rectifier = ~2 x 0.7 = ~1.4V, giving a DC supply voltage to the voltage regulator of V_S = ~15.6V.
- Voltage across zener diode = 12V, leaving 15.6 - 12 = ~3.6V across resistor R.

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 = 86.3Ω. The investigation used 220Ω.
When 3.6V is dropped across it, current through it = 3.6/220 = 16mA. This dissipates 16 x 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:

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



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.

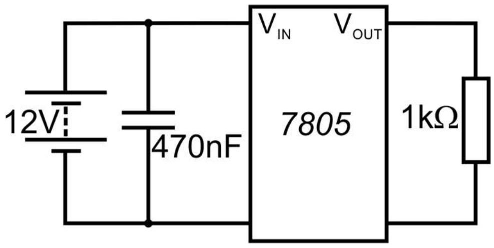
	Linear	**Switching**
Action	Step-down (buck) only	Step-up (boost) **OR** step-down (buck)
Efficiency	Low - depends on (V_{IN} - V_{OUT})	High
Component count	Low	High
Size	Small (without heat-sink)	Large
Noise	Low	High - due to rapid switching
Cost	Low	High

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



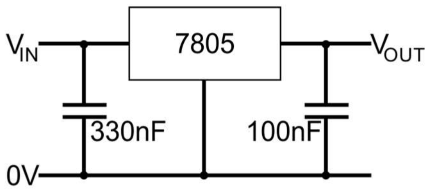
Power efficiency = (Output power / Input power) x 100%
= (V_{OUT} x I_{OUT} / V_{IN} x I_{IN}) x 100%
= ……………….. %

Part 2:

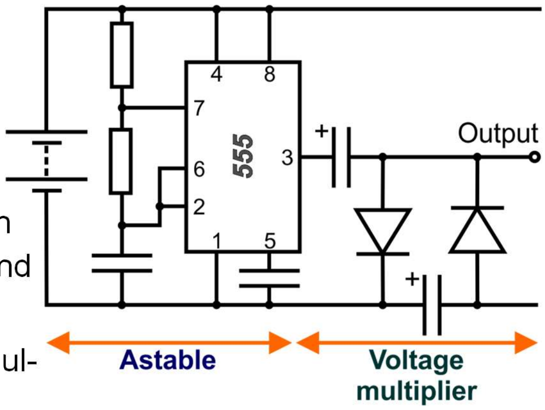
V_{IN} in V	3	4	5	6	7	8	9	10
V_{OUT} in V								

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.



Worksheet 21- The level shifter:

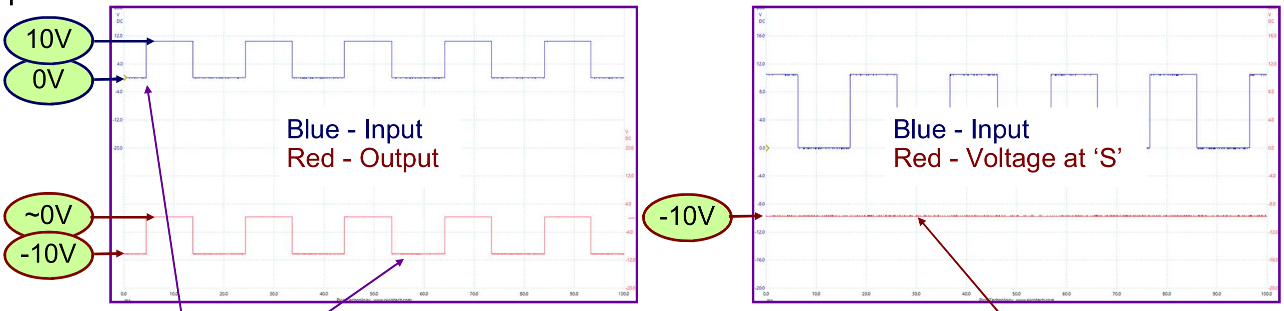


The circuit consists of two sections:

- 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.



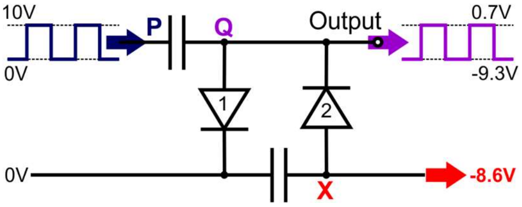
The output signal is a copy of the input, but at different voltage levels.

The signal from point 'S' is a steady voltage at approximately -10V.

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.

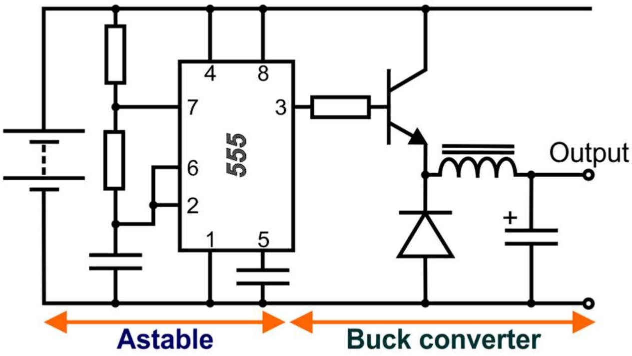
The output signal is the signal at **Q** - a square wave oscillating between -9.3V and +0.7V.

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.

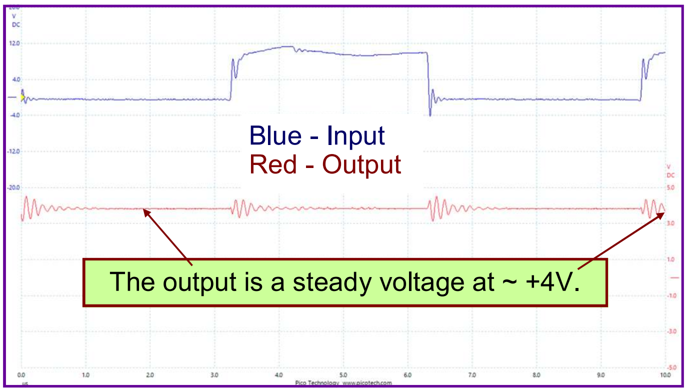
Worksheet 22- The buck converter:

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.

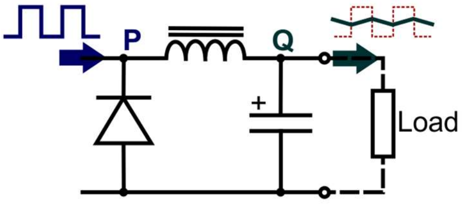
The traces, obtained from the circuit, show a steady 4V output. They also show ‘ringing’ in response to the sudden steps in voltage produced by the square wave, caused by stray capacitance and inductance in the circuit.



The output is a steady voltage at ~ +4V.

The analysis:

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.

Challenge:

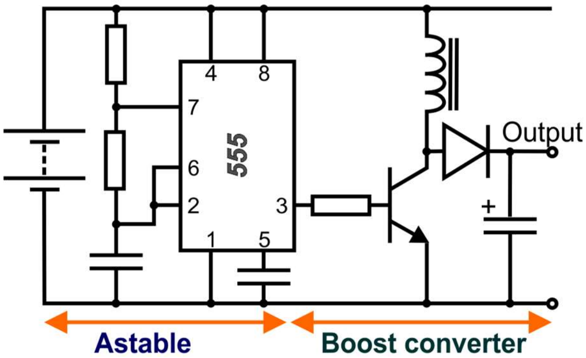
How can you test whether the output is load regulated?

……………………………………………………………………………………………..

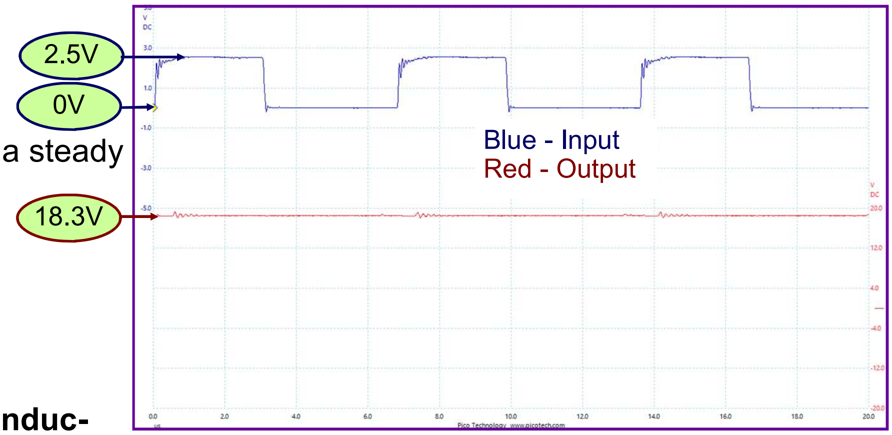
……………………………………………………………………………………………..

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.



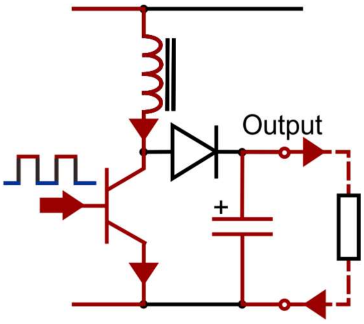
These traces, obtained from the boost converter circuit, show a steady 18.3V output signal.



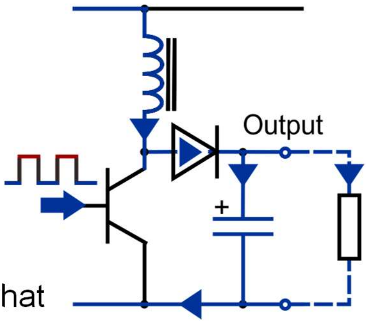
The analysis:

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

……………………………………………………………………………………………………..

……………………………………………………………………………………………………..

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.

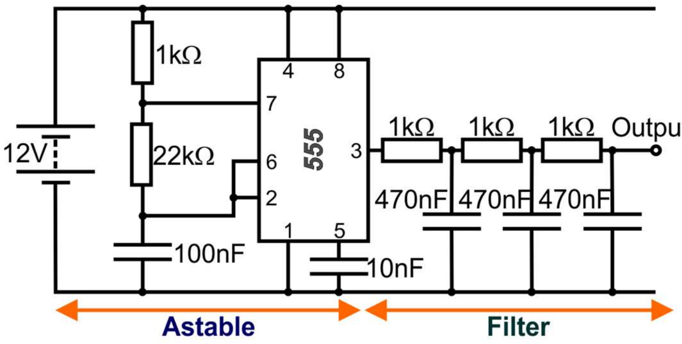
According to Fourier's theorem, a signal like a square wave can be created by combining a series of sine waves of different frequencies and amplitudes. (A sine wave is considered to be the simplest signal, as it contains only one frequency of oscillation.)

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.

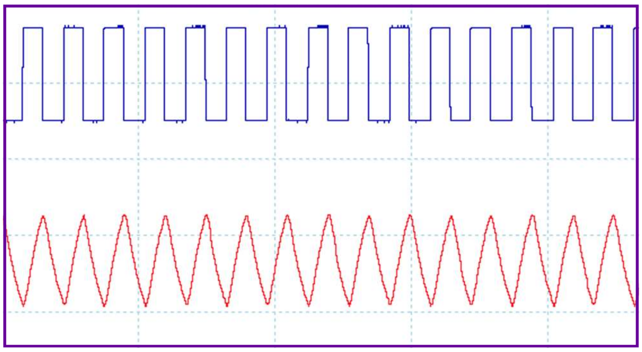
In this investigation, the inverter circuit consists of two sections:

- 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!



Power
And Energy
Electronics

Instructor
Guide

About this course

Introduction

The course is essentially a practical one. Where possible, practical implications and applications of the theory are highlighted to make the course more relevant to the students.
Locktronics equipment makes it simple to construct and test electrical circuits. The result mirrors the circuit diagram, thanks to the circuit symbols printed on the carriers.
A Student Handbook is included to give students a concise record of their studies.

Aim

The course introduces students to concepts and devices used in a range of systems used to deliver and control electrical power. It covers much of the content of Unit 17 - Power and Energy Electronics in the BTEC Level 3 Diploma in Electrical and Electronic Engineering, and similar qualifications, building on the work in module: LK 8392 - 'AC principles'.
Other modules relevant to the Diploma course are:

LK9392 - 'Introduction to digital electronics';
LK8749 - 'Advanced electrical principles - AC';
LK3061 - 'Operational amplifiers';
LK9945 - 'Sequential logic';
LK8473 - 'Advanced electrical principles - DC';
LK2686 - 'Three-phase systems';
LK2094 - 'Combinational logic';
LK4403 - 'Transistor amplifiers'.

Prior Knowledge

It is recommended that students have followed the 'Electricity Matters 1', 'Electricity Matters 2' courses, or have equivalent knowledge, covering the basic electrical concepts of current, voltage and resistance, energy and power and are able to construct and test circuits, using a multimeters, function generators and oscilloscopes.

Using this course:

The experiments in this course should be integrated with teaching to introduce the theory behind it, and reinforced with written examples, assignments and calculations.

The worksheets can be printed / photocopied / laminated, preferably in colour, for the students' use. They are unlikely to need their own permanent copy of the worksheets, but the instructor may choose to distribute copies of the Introduction for students' records.
Each worksheet has:

- an introduction to the topic under investigation;
- step-by-step instructions for the investigation that follows;
- a section headed 'So What', to collate and summarise results, offer extension work and encourage development of ideas, through collaboration with partners and with the instructor.

This format encourages self-study, with students working at a rate that suits their ability. The instructor should monitor that students' understanding keeps pace with their progress through the worksheets. One way to do so is to 'sign off' each worksheet, as a student completes it, and in doing so have a brief chat with the student to assess grasp of the ideas involved in the exercises it contains.

Time:

It should take students between 10 and 15 hours to complete the worksheets. (A similar length of time will be needed to support the learning that takes place as a result.)

Learning Objectives

On successful completion of this course the student will be able to:

- describe the properties of an ideal diode, including the use of a graph;
- use a I/V graph to describe the performance of a zener diode;
- draw the circuit diagram for a zener-diode based voltage reference sub-system;
- identify the terminals of a BJT and distinguish between npn and pnp forms in terms of current flow;
- describe the FET family, including JFETs and enhancement mode an depletion mode MOSFETs;
- identify the terminals of a MOSFET and distinguish between The JFET and MOSFET in terms of the stucture;
- explain why a BJT is classed as a current-controlled device;
- explain why a MOSFET is classed as a voltage-controlled device;
- distinguish between depletion-mode and enhancement-mode MOSFETs in terms of current flow
- identify the terminals of a thyristor and state the conditions needed for conduction to take place;
- identify the terminals of a triac and state one advantage of it over the thyristor;
- state the conduction properties of a diac;
- identify and draw the circuit symbols for:
  pn-junction diode and LED, npn and pnp BJTs, diac, n-channel and p-channel enhancement-mode MOSFETs, n-channel and p-channel depletion-mode MOSFETs, thyristor, and triac.
- identify the anode and cathode of a power diode and a LED;
- distinguish between ‘forward’ and ‘reverse’ bias in a semiconducting diode;
- state the conditions needed for conduction in a semiconducting diode;
- state the accepted value for the forward voltage drop in a silicon pn diode and a LED;
- describe, in terms of voltages, the two states in a switching device;
- describe the relationship between base current and collector current in a common-emitter configured BJT;
- explain the need for a flywheel diode when switching inductive loads such as a motor;
- draw the circuit diagram for a BJT switch;
- draw the circuit diagram for a MOSFET switch, using a n-channel enhancement-mode MOSFET;
- give one potential advantage of the MOSFET switch over the BJT switch;
- explain the term ‘r_{DSON}’ and describe its significance for power dissipation in the MOSFET;
- explain the need for rapid transition between ‘off’ and ‘on’ states in a power switching circuit;
- explain why thyristors make excellent power switching devices;
- draw the circuit diagram for a DC thyristor switch, including capacitor commutation;
- explain the use of capacitor commutation to switch off a thyristor in a DC switching circuit;
- distinguish between the switching properties of a thyristor and a BJT;
- give two advantages of the thyristor switch compared to the electromagnetic relay switch;
- draw the circuit diagram for a H-bridge using n-channel enhancement-mode MOSFETs to control a motor;
- explain how the H-bridge circuit controls the direction of rotation of a motor;
- explain the significance of the term ‘voltage follower’ for a BJT emitter follower;
- draw the circuit diagram for an emitter follower circuit used to control the speed of a motor;
- calculate the voltage gain, current gain and power gain for an emitter follower, given appropriate data;
- explain the need for a darlington driver and draw the circuit diagram for one which uses two npn BJTs;
- calculate the voltage gain, current gain and power gain for a darlington driver, given appropriate data;
- give two advantages and two disadvantages of the darlington pair circuit over the single BJT emitter follower;
- draw the circuit diagram for a MOSFET source follower circuit used to control the speed of a motor;
- calculate the voltage gain, current gain and power gain for a source follower, given appropriate data;
- give four advantages of the source follower circuit over the BJT emitter follower;

continued on following page...

Learning Objectives - continued…

On successful completion of this course the student will be able to:

- explain the principle of PWM motor control and define the terms ‘mark’, ‘space’ and ‘duty cycle’;
- explain why PWM offers greater energy efficiency than the use of a series resistor in motor speed control;
- calculate the ‘mark:space’ ratio for a given PWM trace;
- explain the principle of phase control, used in triggering thyristors and triacs;
- draw the circuit diagram for a thyristor (and triac) circuit using phase control to vary the brightness of a lamp;
- interpret traces for the signals across the capacitor, thyristor (triac) and load in a phase-shift circuit;
- describe the advantage of adding a UJT or diac, to the gate circuit of a thyristor (or triac);
- draw the circuit diagram for a UJT oscillator and explain its operation;
- explain what is meant by ‘rectification’ and why it is usually necessary for modern electronic systems;
- distinguish between half-wave, controlled half-wave and full-wave rectification;
- draw the circuit diagrams for half-wave, controlled half-wave and full-wave rectifiers;
- explain the term ‘ripple’ voltage and state three factors affecting its size;
- describe the need for ‘smoothing’ (or ‘reservoir’) capacitors in rectifier circuits;
- draw the circuit diagram for an astable based on a 555 timer IC;
- state two uses for a voltage multiplier;
- draw the circuit diagram for, and explain the operation of, a voltage multiplier;
- explain the need for a buffer where the output of a voltage multiplier is used to deliver current;
- state the function of a buck converter;
- draw and describe the circuit used to turn square pulses into a low voltage DC output;
- explain the role of capacitors, inductors and diodes in voltage conversion systems;
- state one use for a boost converter;
- describe and explain the production of the output signal expected from a boost converter;
- define the terms ‘line regulation’ and ‘load regulation’ applied to voltage regulation;
- draw the circuit diagram for a zener-diode based voltage regulator;
- explain why such a regulator has a maximum permitted output current;
- calculate the power dissipated in a zener diode and its series resistor under given conditions;
- distinguish between ‘linear’ and ‘switched’ voltage regulators;
- explain how electrical noise can be eliminated from the output of a voltage regulator;
- explain what is meant by an ‘inverter’ and describe three uses for it in electrical power systems.
- explain the function of the low-pass filter in an inverter;

What the student will need:

To complete the course, each group of students will need the following Locktronics equipment:

2	LK8900 Locktronics Baseboard
2	LK6207 push-to-make switch carriers
1	LK7936 Universal component carrier
1	LK5291 MES bulbholder
1	LK4025 10Ω resistor carrier
1	LK5206 120Ω resistor carrier
1	LK5215 220Ω resistor carrier
4	LK5202 1kΩ resistor carriers
1	LK5209 5.6kΩ resistor carrier
1	LK6211 22kΩ resistor carrier
1	LK5218 100kΩ resistor carrier
1	LK5208 250Ω potentiometer carrier
1	LK5219 100kΩ potentiometer carrier
1	LK5222 100nF capacitor carrier
2	LK5221 10μF capacitor carriers
1	LK6202 100uF capacitor carrier
1	LK6214R3 5mH choke
1	LK5254 8.2V zener diode
1	LK6635 LED (red) carrier
1	LK7208 7805 voltage regulator
1	LK5248 thyristor
1	LK7290 phototransistor
1	LK5246 UJT
1	LK8275 power supply carrier
1	HP2666 DC power supply
2	LK5609 leads 4mm to 4mm, blue
2	LK5603, leads 4mm to 4mm, red
2	LK5604, leads 4mm to 4mm, black
30	LK5250 connecting links
1	LK6208 changeover switch
1	LK2346 12V MES bulb
1	LK6706 Motor
2	LK4002 100Ω resistor carriers
1	LK5207 180Ω resistor carrier
1	LK5205 270Ω resistor carrier
1	LK6218 2.2kΩ resistor carrier
2	LK5203 10kΩ resistor carriers
1	LK5201 33kΩ resistor carrier
2	LK6200 1MΩ resistor carriers
1	LK5214 10kΩ potentiometer carrier
1	LK6283 100pF capacitor carrier
3	LK6216 470nF capacitor carriers
1	LK5224 47uF capacitor carrier
1	LK6203 2200uF capacitor carrier
4	LK5243 power diodes
1	LK5258 12V zener diode
1	LK5266 bridge rectifier
2	LK5240 transistor, NPN
4	LK8011 power MOSFET carriers
1	LK4051 Triac
1	LK7582 555 carrier
1	LK2340 AC voltage source carrier
1	HP3728 AC power supply

and, in addition:

2	multimeters
1	dual-trace oscilloscope (or Picoscope)

Instructor Guide—Scheme of work

Worksheet	Notes for the Instructor	Time
Introducing the components	This course begins with an overview of the nature of semiconductors and range and types of component used in the course. Much of this information may be familiar to the student. Most will be expanded during the course. The instructor, knowing the students' background can judge the level of support to provide at this point. As minimum, it serves as a reference for the circuit symbols used in the course. Other symbols are used elsewhere. The instructor may wish to broaden the range contained here.	15 - 25 mins
1	Two important aspects to electronics are evident here - understanding how a component or circuit works and being able to select components to create a circuit. The terms 'forward-biased' and 'reverse-biased' are introduced, but may need reinforcement by the instructor. Students investigate conduction in a diode when forward and then reverse-biased and then plot a I/V graph using their results. Even for advanced students, multimeters can be a source of widespread fear and mystery! They are in widespread use because of their low cost and their versatility. Although they differ in terms of the functions they offer and details of their structure, the broad principles are the same for all multimeters. For some students, an introduction, or reminder, about the particular meters in use might be worthwhile Beware! It is common to find that the ammeter settings are protected by an internal fuse. This is frequently 'blown' because pupils switch on the meter, connected as a voltmeter, with the dial turned to a current range. Instructors should check all fuses prior to this exercise, and be prepared with a supply of replacement fuses! A delicate hand is needed to adjust the current through the diode. Conditions change quickly! The power supply is set to 3V to make it unlikely that the diode is damaged by excess current. For the same reason, a 10Ω resistor is connected in series with the diode. The instructor should check that the correct power supply setting and multimeter ranges have been chosen. The student is asked to compare the behaviour of this diode with ideal diode properties outlined in the introduction. The obvious difference is that, under forward bias, conduction does not take place until the voltage exceeds ~0.7V, for a silicon diode. The instructor could allow a fast group to compare the properties of the silicon diode with a germanium diode. The challenge is to carry out the same investigation for a LED. Generally, these are not silicon-based and so have a different forward-voltage drop. The Locktronics LED carrier incorporates a series resistor to protect the LED against excessive current. The next worksheet uses a very similar layout. The instructor may wish to run the two investigations together to save time.	30 - 40 mins

Instructor Guide—Scheme of work

Worksheet	Notes for the Instructor	Time
2	This worksheet takes the study of diodes one step further and prepares the ground for later use of zener diodes. As the introduction says, in many ways these are nor remarkable - they do what other diodes do. However, most commercial power diodes are designed with reverse breakdown voltages so high that they are not accessible to experimentation. Zener diodes break down at low voltage. The procedure is the same as in worksheet 1. In fact, the circuit is virtually identical, so that the layout can be adapted quickly from that used previously. The 'So what' section introduces the idea of power handling, an important quantity in this field of electronics. The instructor may wish to elaborate on the information given here and give sample calculations on power handling and on the use of the zener diode as a voltage reference.	25 - 35 mins
3	The aim is to investigate the use of a transistor as a switch. First of all it is necessary to identify what that means! Switches are 'off' or 'on' but the first task is to identify the electrical properties that define these states. Students build and take voltage measurements on a switch unit to pinpoint these. Then they construct and test the lamp-switching circuit, making voltage measurements to verify that the circuit exhibits the same two states. It is operated by a push-switch but could equally be light-operated or temperature-operated. The effect of the transistor is shown by trying to run the system without it. This approach is artificial, in that it is only the 10kΩ resistor that stops the arrangement from working. However, some sensors have a high internal resistance and would need the addition of the transistor to boost the limited current output from them. In the third challenge, they use the circuit to control a motor. An inverse parallel diode is used to protect the transistor from 'back e.m.f.', the principle of which is explained. Note that a much lower value of base resistor is used to create the increased collector current required to saturate the transistor.	25 - 35 mins
4	MOSFETs are widely used in switching circuits for two reasons - they draw virtually no current from the input source, and can deliver high currents with little power loss, (assuming rapid changeover from the 'off' to the 'on' state). This worksheet looks at its use as a switch. Another common application is in logic gates, in 'CMOS' (Complementary Metal-Oxide-Semiconductor) where 'complementary' refers to the use of 'complementary' n-channel and p-channel transistors. Again, a huge advantage is the low power consumption. (It is assumed that students have studied logic gates previously. Otherwise the instructor will need to expand on this topic.) The second circuit demonstrates the use of a MOSFET as a touch-switch and demonstrates just how small a current is needed to operate the device. The 'So what' section details the conduction process in the MOSFET and compares its performance against that of an ideal switch and a BJT switch. It then focuses on why rapid changeover between the two switching states is desirable in terms of power dissipation. The work in the Student Handbook requires that students have access to the data sheet for the `RFP30N06LE` MOSFET, available from the Fairchild Semi-conductor website. They use the data to calculate the power dissipated in the MOSFET when passing maximum drain current.	30 - 40 mins

Worksheet	Notes for the Instructor	Time
5	This worksheet looks at the use of a thyristor as a switch in a DC circuit. It first identifies the conditions needed to make a thyristor conduct. An important issue, which distinguishes the device from the BJT and MOSFET switch, is that it is self-latching under the right conditions. In DC circuits, this can be a problem, as it cannot be turned off by any signal applied to the gate. This circuit uses capacitor commutation to turn it off. To see the very rapid changes in voltage level caused by pressing switch B, the students use an oscilloscope. This is the first occasion in the module where this is used and I may expose weaknesses in some students' skills. The instructor needs to monitor events closely. The 'So what' section describes how capacitor commutation works, illustrating the explanation with a sample Picoscope trace of the signal involved.	30 - 40 mins
6	So far, the module has examined systems that switch devices on and off. This one extends that by looking at a system which can also control the direction of rotation of a motor - the H-bridge. The introduction shows how this could be achieved using four mechanical switches, with the problem that incorrect use could short-circuit the power supply. However, the diagram is useful in showing the principle behind the circuit. The solution involves four switching devices, MOSFETs in this case, controlled in such a way that it is impossible to short-circuit the supply. The circuit diagram and layout appear complicated partly because of the presence of the four 'flywheel' diodes, whose function was outlined in worksheet 2. It might help if the instructor outlines features of the circuit before the students begin construction. The purpose of the diodes has been mentioned already. The gates of MOSFETs A and C are connected, as are the gates of MOSFETs B and D (to prevent short-circuiting the power supply.) These connections mean that only two 1MΩ pull-down resistors are needed to 'anchor' the gates to 0V when not connected to the positive rail by the changeover switch. When MOSFETs A and C are on, A connects the left-hand side of the motor to 12V, while C connects the right-hand side to 0V. When B and D are switched on, these connections are reversed. The diagrams in the 'So what' section show the current path for both switch positions. Obviously, instructors need to pay close attention to the students' layouts! The suggested layout uses two baseboards. In all other worksheets, only one baseboard is needed. Where students are allowed to work at their own pace, a few extra baseboards for the group will allow this to happen seamlessly. Alternatively, the order in which different groups proceed can be manipulated so that a few extra baseboards can be utilised to meet the demand.	30 - 40 mins

Work-sheet	Notes for the Instructor	Time
7	Now the focus changes from on/off control to graduated control - in this case, graduated control of motor speed. The circuit under investigation is known as a common-collector amplifier. The base terminal is the input, the emitter terminal the output and the collector terminal is common to both input and output. The instructor can expand on these terms, contrasting it to the transistor switch circuit is worksheet 2, to ensure that students appreciate that the function of this circuit is different. This is a power amplifier circuit. Although the voltage gain is ~unity, there is a large current gain, giving a large overall power gain. The first step is for students to appreciate the meaning of ‘follower’, a term used for a number of subsystems in electronics. Looking at their voltmeter readings, they see that as the input voltage changes, the output follows, (with a small difference between them due to the forward voltage drop across the base-emitter junction of the transistor). It is also shown that the circuit does not respond to negative voltages. The results are analysed in the ‘So what’ section, first plotted as a graph and then used to obtain the power gain (= voltage gain x current gain) for the emitter follower.	30 - 40 mins
8	An extension to the work done in Worksheet 7, two transistors are coupled together to give greater current gain. So useful is this arrangement that a ‘darlington pair’ can be purchased as apparently a single device. The base terminal is the base of the first transistor, the emitter terminal the emitter of the second transistor and the collector terminal the connected collectors of both transistors. In general, the first transistor does not handle appreciable power and so can have a small power rating. The second transistor, however, must have a high power rating. The advantage of this arrangement is that only a tiny current is needed to operate the circuit. The voltage drop across the transistor pair is greater (around double) leading to a smaller voltage gain. However, the overall current gain is equal to the product of the individual current gains. It is huge! That leads to a similarly huge power gain. Viewed in a different way, a change in the output current is achieved by a very small change in input current to the pair. In other words, the pair appear to have a very desirable high input impedance. Students may or may not be familiar with the term ‘impedance’. The instructor will choose to develop, or ignore, the concept at this stage, depending on the students’ ability and experience. The procedure is the same as that for worksheet 6 and leads to a calculation of the power gain for this circuit. The challenge is to demonstrate the ability of the darlington driver to work off extremely low input currents by controlling it from a light sensor based on a phototransistor.	30 - 40 mins

Worksheet	Notes for the Instructor	Time
9	Still focussing on graduated control - controlling motor speed, this circuit is the mirror image of the emitter follower. For parallel reasons, the arrangement is also called a common-drain amplifier. The procedure is identical to that used for the emitter follower (positive input voltages only.) The emitter follower and source follower are examples of a buffer amplifier, a subsystem that interfaces two subsystems so that signals pass efficiently between them. The buffer amplifier should look like a huge impedance to the subsystem on its input (and so draw very little current from it) but look like a tiny impedance to the subsystem that follows it (and drop little of the output voltage across the buffer itself when a current is drawn from its output). Students are asked to compare the performances of the source and emitter follower - a good homework task! • As is shown using sample data, the power gain of the source follower is higher than the BJT equivalent, because the input current is much smaller . • However, it does involve a bigger voltage drop. • Compared to the emitter follower, the source follower has a much higher input impedance, but not quite as low an output impedance. • It is less prone to thermal runaway, where an increase in temperature leads to an increase in current which, in turn, leads to a further increase in temperature ……. .	30 - 40 mins
10	This topic is a significant departure from previous ones. It is a digital means of controlling output voltage, whereas the others have been analogue. In this investigation, it is used to control motor speed, but could equally well control the brightness of a lamp, temperature of a heater etc. It offers two significant advantages. Being digital, it can be generated from a programmable device like a microcontroller. As it is a series of ‘off’ and ‘on’ signals, ideally no power is dissipated in the switching device - all the power is transferred to the controlled device. The students capture waveforms using an oscilloscope to show the effect of adjusting the 100kΩ ‘pot’. They may not get the best results by adjusting it from one extreme to the other. Hence the instruction “...fully clockwise (almost!) .” and “...(almost) fully anti-clockwise.” They need to use judgement to get the best results. The section introduces several terms related to PWM - ‘mark’, ‘space’, ‘mark:space ratio’ and ‘duty cycle’. The instructor may wish to reinforce the work done in the investigation with other examples with differing values of ‘mark’ and ‘space’.	30 - 40 mins

Instructor Guide—Scheme of work

Work-sheet	Notes for the Instructor	Time
11	This worksheet is all about AC theory! It brings in the concepts of phase, phase lag, phase difference and their measurement. Depending on the students' previous experience, the instructor may decide that an introduction to AC theory would be beneficial. It could include the mechanism of capacitance, leading to explanations of why the voltage across the capacitor lags behind that of the AC supply and why the amplitude of the voltage across the capacitor gets smaller as the phase difference increases. The students should be allowed sufficient time to obtain clear oscilloscope traces of the signals across the AC supply and across the capacitor for two different positions of the variable resistor. They are challenged to investigate the effect of different capacitor and resistor values on the size of the phase lag. Again, they need time if they are to absorb what is happening. Where the AC supply has a peak value greater than 20V, the 'X10' setting on the probes should be used. The instructor should explain the effect of this to the students as otherwise they may misinterpret the voltage scale.	20 - 30 mins
12	The subsystem studied in the previous worksheet is used to control the switching of a thyristor. The instructor could begin by reminding students of the conditions needed to make the thyristor conduct. The supply is now AC, so turning off the thyristor is not a problem - no need for capacitor commutation! It happens when the AC supply voltage reverses (or a little before, when the anode current drops below the holding current of the thyristor). As previously, students need time to 'play' with different resistor settings to feel comfortable with what is happening and obtain good oscilloscope traces. The analysis identifies some issues specific to the equipment being used - the 'spikes' on the AC supply, the distorted shape of the signals and the need for using the 'X10' probe setting.	20 - 30 mins
13	One outcome of the previous investigation is that the thyristor conducts only on the 'positive' half-cycle of the AC supply. It can deliver power to the load for a maximum of 50% of the time. To increase efficiency, a triac is used, (TRIode for Alternating Current,) which allows bidirectional current flow. This investigation uses the same circuit as the previous except that the thyristor is replaced by a triac. (Think of it as two thyristors connected in inverse parallel with a common gate.) Once again, students need time to 'explore'. Triacs are asymmetrical in their triggering. In theory, they start conducting at the same point in both 'positive' and 'negative' half-cycles of the AC supply, leading to a symmetrical trace on the oscilloscope. In practice, they conduct earlier in one half-cycle than the other. A student may be unlucky, especially if rushed, and see what looks like the signal from a thyristor - conduction in one half-cycle only. Hence the need for time, and encouragement, to explore. Using a diac (Diode for AC) reduces this asymmetry (and the undesirable harmonics in the output that result.) This is difficult to investigate as diacs operate typically at voltages ~30V - beyond the range of the AC supply we are using. Where an institution has a power supply offering higher outputs, students could investigate the effect of adding a diac in series with the gate. Effects similar to those in the last investigation are seen in the resulting signals, caused by the limitations in the power supply.	20 - 30 mins

Work-sheet	Notes for the Instructor	Time
14	The UJT has a relatively simple structure, described in the introduction. When ‘switched off’, it has a high resistance of a few kilohms. When a big enough positive voltage is applied to its emitter, a current, (i.e. a large number of ‘free’ charges, flows into the lower section of the UJT, substantially reducing its resistance. In the oscillator circuit, the voltage at the emitter is that across the capacitor. Initially, this charges up through the 5.6kΩ resistor and variable resistor, largely unaffected by the high resistance of the part of the UJT in parallel with it and 180Ω resistor. Eventually, the capacitor voltage is big enough to force the emitter / base 1 junction into conduction. The resulting influx of charge carriers reduces the resistance of the lower section of the UJT so much that the capacitor now discharges through it. Soon, the capacitor voltage is too small to maintain conduction and the resistance of the UJT rises again. The cycle continues. This explanation should be accessible to most students, provided they have a reasonable grasp of conduction in semiconductors. The instructor may need to support some students, however. Choosing the right resistor values for the resistors in series with the UJT is important. A current flows through the UJT and them even when the UJT is ‘off’. The resistors are chosen so that the resulting voltage at base 1 is not so small that conduction through the emitter / base 1 junction is virtually continuous, nor so large that it never happens. Quicker, more able groups could be asked to investigate what happens for a range of resistor values.	20 - 30 mins
15	The core issue here is power dissipation in a switching device. As pointed out earlier, for an ideal switching device: • When switched off, the current is zero and so the power dissipated in the switching device is zero. • When switched on, the voltage across the switch is zero and so the power dissipated in it is still zero. The critical nature of the turn-on / turn-off process can not be appreciated in this investigation because of the low voltages and currents used in it. Without the UJT oscillator, the thyristor is switched on by the relatively slowly rising voltage across the capacitor (a sinusoidal signal). It is switched off by another sinusoidal signal, the AC power supply. The finite rise-times of these signals slow down the switching process and increase the power dissipated in the thyristor. The output signal from the UJT, however, is virtually a spike - an almost infinite rise-time. Applied to the gate, it snaps the thyristor into conduction extremely rapidly. This feature is so important where large voltages and currents are concerned that the instructor should go to significant lengths, using written questions, group discussions, classroom displays etc. to drive it home to the students.	20 - 30 mins

Instructor Guide—Scheme of work

Work-sheet	Notes for the Instructor	Time
16	Rectification is the process of converting AC to DC. There are several ways to implement it. We look at three - half-wave, controlled half-wave and full-wave rectification. First we look at half-wave rectification. The students may need reminding about the significance of voltage/time graphs. The current changes direction only when the trace crosses the 0V line. (A popular misconception is that it changes direction at the peak of the voltage signal.) If it never crosses 0V, then the current is DC, but may not necessarily be steady DC. Half-wave rectification uses the one-way conduction property of a diode, to ensure that the current through the load never reverses i.e. is always DC. The circuit is simple - just add a diode in series with the load. However, it is not very efficient, as no current at all flows during the negative half-cycle of the AC supply. It rectifies only half of the AC ‘wave’, no more, no less, as the top graph on p.40 shows. When this is not an issue, a simple battery charger, for example, then use half-wave rectification. The half-wave rectifier does not provide smooth DC. There is a large ripple voltage (variation in output voltage.) This can be reduced substantially by adding a high value capacitor in parallel with the load. To keep the size down, this is usually an electrolytic capacitor, and so care must be taken to ensure that it is connected the right way round, as stated in the instructions. (The instructor must check that this warning is implemented.) The size of the ripple voltage depends on the output current, the frequency of the AC supply and the size of the smoothing capacitor. The results show that the output is 0.7V lower because the output is shared between the conducting diode (0.7V forward-voltage drop) and the load.	20 - 30 mins
17	Controlled half-wave rectification adds another level of sophistication - the ability to vary the DC output voltage. It is accomplished by replacing the diode with a thyristor (sometimes called a SCR - silicon controlled rectifier.) The first circuit demonstrates that rectification is controlled by the thyristor gate. However, it is on / off control. The modification adds graduated control. The 100Ω resistor and variable resistor output a fraction of the AC supply to the thyristor gate. This fraction depends on the setting of the variable resistor. As the supply voltage increases, the gate voltage increases. This is not an easy concept and students may need support in grasping it. There is effectively a single p-n junction between the gate and the cathode so that eventually the gate voltage turns on this junction and the thyristor begins to conduct. Adjusting the variable resistor changes the fraction of the supply applied to the gate and so changes the point at which the thyristor conducts in each cycle of the AC supply. This effect is shown in the sample traces. They also show the effect of smoothing this signal. To help with answering the questions in the Student Handbook, the instructor could have copies of the thyristor datasheet to hand.	25-40 mins

Worksheet	Notes for the Instructor	Time
18	Now the student investigates full-wave rectification. As its name suggests, it makes use of both the positive and negative half-cycles of the AC supply. A DC current can flow all the time through the load, making more efficient use of the supply. This improved efficiency comes at the price of more complex circuitry. At least four diodes are used to rectify the AC supply. The instructor should ensure that students understand that the output is DC. (The traces they obtain may look a bit like AC!) Equally, they need to appreciate that the circuit they have constructed is delivering an output current to the load (1kΩ resistor.) The size of this current has consequences for the ripple voltage. The size of smoothing capacitor needed depends on how big the output current is. Faster groups could be set the task of investigating the effect of different values of load resistor on ripple current. Students should compare the ripple current from the half-wave rectifier with that from the full-wave circuit. The frequency of the latter is twice as big and this reduces the amplitude of the ripple. It is important that students do not try to use two Picoscope input channels to capture two signals at the same time. The outer casing of the BNC connectors are joined. Using two inputs, connected to different parts of a circuit, can short-circuit those parts. This is discussed on page 43, using a circuit diagram of the full-wave rectifier to make the issue clearer. However, instructors may wish to discuss this problem with students because of its wider implications for the use of test instruments.	20 - 30 mins
19	The next two worksheets focus on voltage regulation - the need to keep the power supply voltage constant. There are two measures of this, known as line regulation and load regulation. Both are equally important but cover different aspects of a power supply's performance. Good line regulation means that the output voltage is immune to changes in the 'line' (input) voltage. Good load regulation means that the output voltage is immune to changes in output current, brought about by the use of different loads. The first version of voltage regulator uses discrete components all of which have been investigated in earlier worksheets. Students should see this as a combination of a full-wave rectifier, a smoothing capacitor and a zener diode. The measurements they take allow them to assess the load regulation of the system. It is not easy with this setup to examine the line regulation, though they will do so with the next regulator. Where the institution has a variable voltage AC supply, this could be used instead of the HP3728 AC power supply to study the effect of different line voltages.	20-30 mins

Instructor Guide—Scheme of work

Work-sheet	Notes for the Instructor	Time
20	A number of dedicated voltage regulators are available. Here the ‘7805’, the 5V member of the ‘78XX’ series is investigated. We are not interested in its internal structure, only its performance. It is described as a linear regulator. The instructor may choose to spend time at this point distinguishing between linear and switching regulators. The ‘So what’ section includes a table listing some features of each. In practice it is advisable to have capacitors across both the input and output to eliminate noise. In this case, we protect only the input in this way, as any noise in the output will not affect our readings. In the first part of the investigation, students take readings of input and output voltage and current to allow them to calculate the efficiency of the 7805. They should notice one feature of the regulator - that there is a substantial voltage drop across (and so energy dissipation in) the device. In the second part, the task is to assess the line regulation of the regulator. The challenge is carry out measurements to assess the load regulation of the device. Instructors may choose to give this as an extension task to faster groups or to do it as a class exercise, with each group taking a different value of load resistor and then pooling the results.	25-35 mins
21 - 24	The next four worksheets study aspects of voltage regulators and power supplies. All are driven by 555 astable subsystems. To speed progress through them, it is suggested that the students build the astable on one baseboard and keep it throughout. The odd component value changes to optimise the frequency to suit the particular worksheet but this approach streamlines progress. Then add the relevant subsystem under investigation on the second baseboard and attach it to the astable.	
21	Level shifter circuits vary a lot in their design. Basically, they need an pulse generator, a device which switches on and off repeatedly and rapidly. For this investigation, it is a 555 astable. In some designs, this pulse generator is shown as a simple switch. The clever part of the design is the voltage multiplier. Its effect is rather like that of a mechanical ratchet. It relies on the two properties of components: • the forward voltage drop across a silicon diode is clamped at 0.7V, no matter how much current flows through it (providing it doesn’t melt!); • a voltage ‘step’ passes straight through a capacitor, because it doesn’t allow time for a current to flow, moving charge to or from its plates. The instructor may need to spend time supporting these ideas to ensure that students understand them. The sample traces show the two effects of the circuit: • to output a mirror image of the input, but moved to new voltage levels; • to create a new power rail at a different voltage to the input power rails. (If the new power rail is to be used, it must be buffered to reduce the current flowing into or out of it.) It is important that students understand how the voltage multiplier works. The instructor may need to spend time with weaker students emphasising the steps outlined in the analysis section. The instructor could set a fact-finding task looking at voltage multipliers, used either singly or cascaded together.	30-45 mins

Work-sheet	Notes for the Instructor	Time
22 - 23	These two worksheets cover related topics. The two systems are often combined in a single package, a buck-boost converter, sharing common components. As pointed out for the level shifter, there are a variety of approaches to designing buck and boost converters, depending on the target application and desired outcome. The aim here is to illustrate the principle. There are features common to all buck and boost designs - especially the use of a current buffer, inductors and capacitors. The analysis outlines general aspects of their behaviour, transferable to other circuits. The aim is to do so without mentioning 'reactance' and 'impedance', which are felt to strike fear into the hearts of students. The inductor and capacitor are mirror-images of each other. The inductor stores energy in a magnetic field, the capacitor in an electric field. It hinders high frequency AC more than low frequency AC. The capacitor has the opposite behaviour. In an inductor, the current rises and falls exponentially. In a capacitor, the voltage across the plates rises and falls exponentially. The capacitor hinders high frequency AC more than low frequency AC. The use of a pulse generator at high frequency allows for smaller and lighter inductors and capacitors, reducing the overall size and weight of the device. With the buck converter, the first hurdle to overcome is the feeling that a couple of resistors would do the job very nicely anyway! The issue is energy efficiency - we don't want to waste energy, just repackage it at a different voltage and a couple of resistors don't come near! Efficiencies well over 90% are achievable in a well-designed buck converter. The investigation initially uses an astable frequency around 200kHz, resulting in a reasonably steady output voltage. Faster groups can investigate the effect of using a bigger capacitor to reduce the astable frequency or look at the load regulation by changing the load resistor. The harsh reality for the boost converter - because it steps up the voltage, it must step down the current. Otherwise it violates the law of the conservation of energy. In this respect, it is like the step-up transformer. The analysis looks at the two situations, showing current paths when the buffer transistor is 'off' and then when it is 'on'. For both systems, students could be asked to measure the efficiency, by measuring the input and output voltages and currents.	20-30 mins each

Worksheet	Notes for the Instructor	Time
24	At this point the emphasis changes. Earlier worksheets looked at AC to DC (rectification) and then DC to DC conversion. Here it is DC to AC conversion. We need to mention a complex mathematical theorem at this point, Fourier's theorem. All periodic signals (i.e. those that repeat over and over in a regular manner) can be made by adding together the right mixture of sinusoidal signals, (in terms of amplitude, frequency and phase). The square pulses from the astable, then, are a mixture of many sinusoidal signals. The lowest frequency sinusoidal component has the same frequency as the square pulses and is called the fundamental. The higher frequency components are called harmonics. One advantage of using the Picoscope is that it includes a spectrum analyser, which will reveal the higher frequency harmonics in the square wave. The instructor could project traces of different types of signals - sinusoidal, square, triangular etc. in introducing Fourier's idea. The system first uses DC power to create square pulses (using the astable.) These are filtered to remove all but the fundamental. This is a sine wave. We have converted DC to sinusoidal AC. The instructor may need to discuss how low pass filters work in terms of capacitors offering little hindrance to high frequencies, which then flow to ground, whereas inductors offer little hindrance to low frequencies, which pass on to the output. In reality, the filter used here is not selective enough to leave only the fundamental. However, the traces produced look quite good.	25-35 mins
Introducing the digital oscilloscope	The course assumes that students have access to dual-trace oscilloscopes, or their equivalent, like the 'Picoscope'. These are computer-based and allow the students to save their traces for future reference. The instructor could use some of these samples during tutorial work to make appropriate points. This section includes a guide to using the Picoscope. Much of this will be relevant to other types of oscilloscope. For some students, a brief tutorial on using an oscilloscope will help them to feel confident enough to use it.	

Introducing the digital oscilloscope

The oscilloscope (CRO):

monitors signals, that vary over time and presents the results as a voltage/time graph.

The basic controls are:

- Voltage sensitivity - sets the scale on the voltage (vertical) axis;
  - spreads the trace vertically if a lower number is used. The diagram shows a setting of 0.5 V/div.
- Timebase - sets the scale on the time (horizontal) axis.
  - spreads the trace horizontally if a lower number is used. The diagram uses a scale of 10 ms/div.
- Trigger - sets the threshold signal voltage that starts data-gathering;
  - can be set for either a rising or a falling signal at that voltage level.

The digital oscilloscope:

Computer-based oscilloscopes, like Picoscope, are data-loggers. They monitor voltages, at regular intervals, and pass the results to software in the computer.

There, it is processed to produce voltage / time graphs, frequency information etc. to be displayed on the monitor, stored as a file, or printed, like other information on the computer.

The Picoscope uses the oscilloscope controls described above, plus:

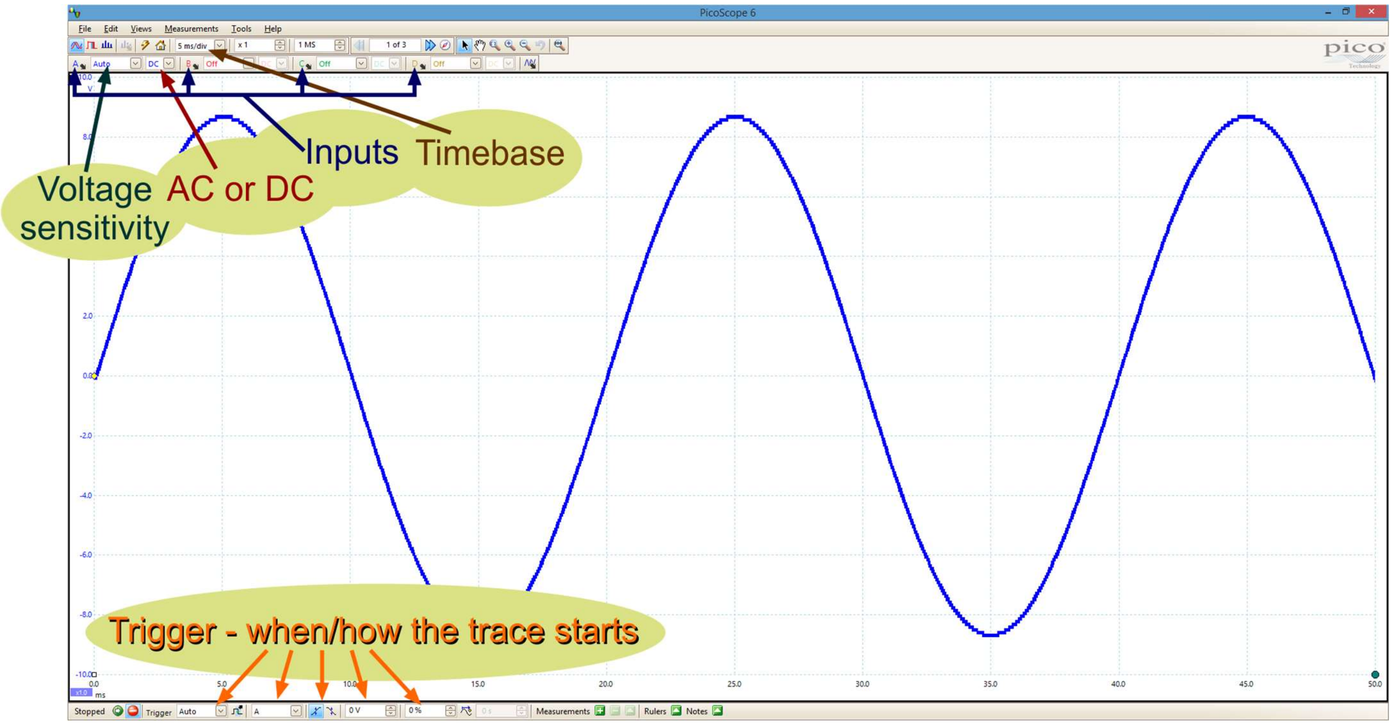
- AC or DC - shows only varying voltages for 'AC' (so centres the trace on 0V;)
  - shows the true voltage levels when DC is chosen.

- Stop / Go - '**Stop**' - the trace is 'frozen' (i.e. can be saved to a file;)
  - '**Go**' - the trace is showing events in real-time;
  - click on the appropriate box to change from one to the other.

Using Picoscope

The settings are selected on-screen using the drop-down boxes provided.

The following diagram shows some of the main controls on the Picoscope 6 screen.

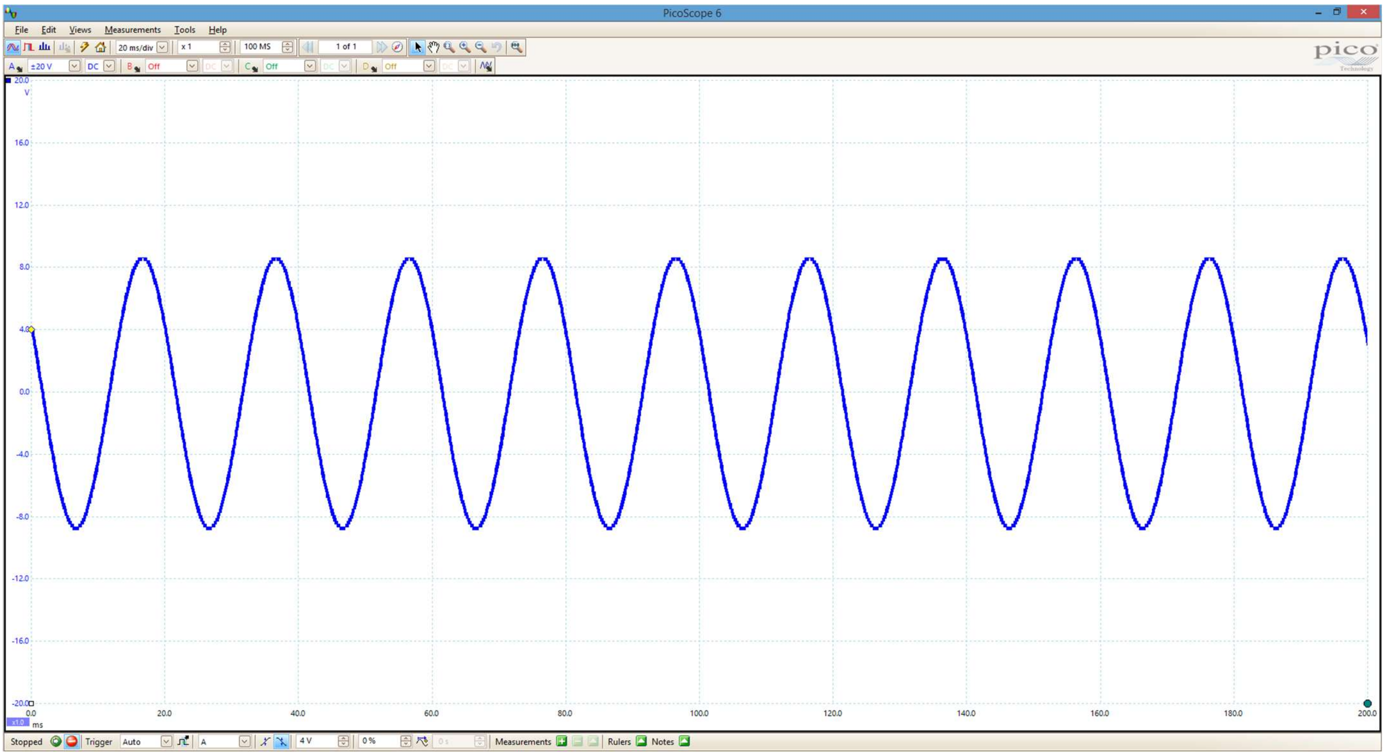


The trace shown above uses the following settings:

Control	Setting	Consequence
Timebase	5 ms/div	time scale (horizontal axis) is marked off in 5 ms steps.
Voltage sensitivity	auto	software adjusts the voltage scale to suit the signal. The scale on the left-hand edge increases in 2V steps. Trace shown has a maximum value of around 8.7V.
Trigger	Auto	shows any changes in the signal as they happen.
	Ch A	channel A signal determines when to start the trace.
	Rising	waits for a rising voltage to reach the threshold
	Threshold - 0 mV	starts when the signal on channel A rises through 0V
	Pre-trigger - 0%	display starts with the very first data captured.

Picoscope continued...

The next trace shows the same signal but some of the settings have been changed.



The new settings are:

Control	Setting	Consequence
Timebase	20 ms/div	time scale is marked off in 20 ms steps.
Voltage sensitivity	4V/div	The voltage scale is marked off in 4V steps. The trace still has a maximum value of around 8.7V.
Trigger	Auto	still shows any changes in the signal as they happen.
	Ch A	channel A still determines when to start the trace.
	Falling	waits for a falling voltage to reach the threshold
	Threshold - 4V	starts when the signal on channel A falls to 4V
	Pre-trigger - 0%	display still starts with the very first data captured.

More information about using Picoscope is given in the Picoscope User manual, found on the CD-ROM that comes with the instrument or on the website www.picotech.com.

Version control

17 10 22	Minor amendments
16 08 23	Reformatted to new style
04 12 23	small amend to BOM P85 to match BOM on system