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Simplifying Electricity

Transistor amplifiers

CP4403

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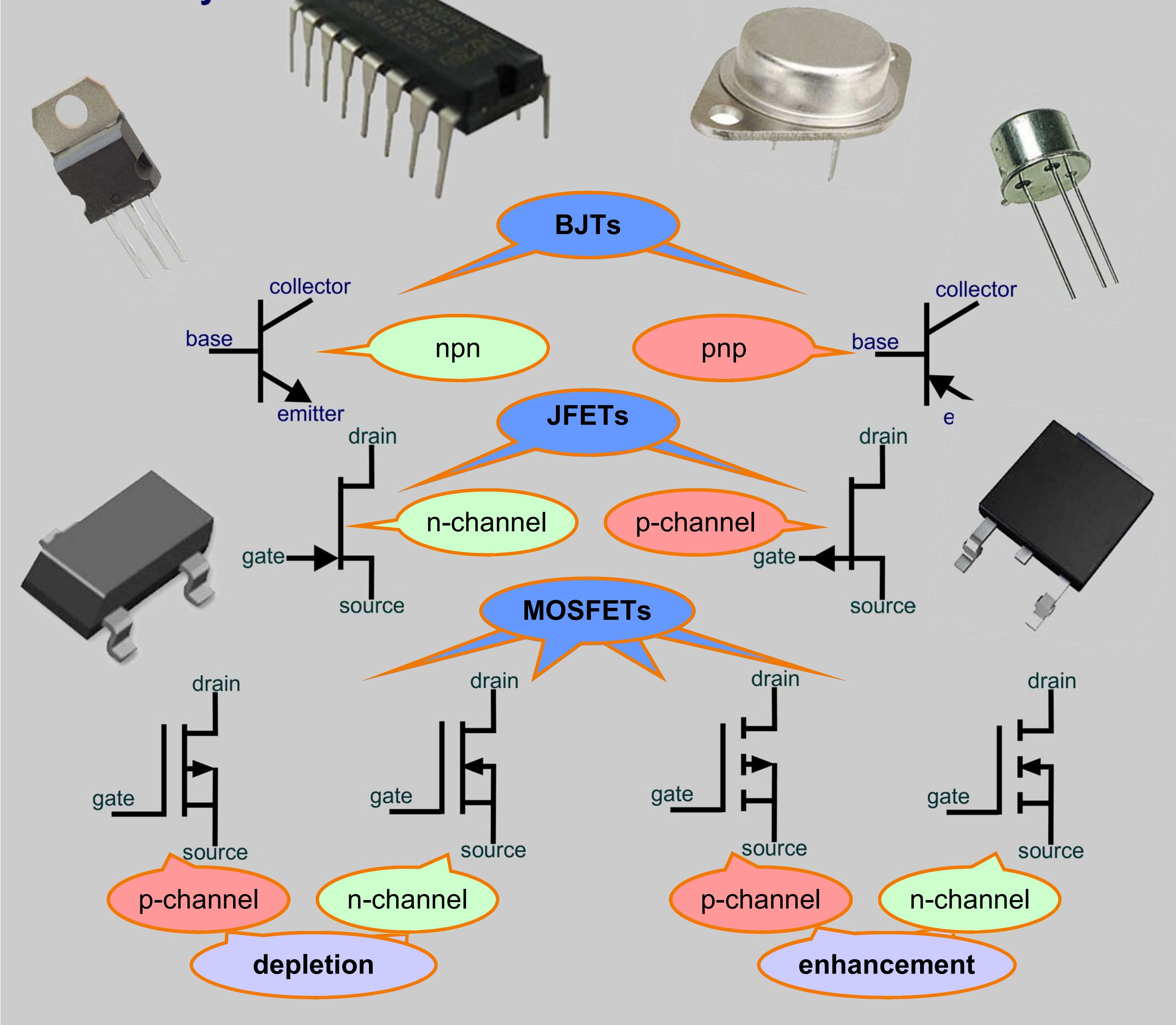
Contents

Introduction

The family:

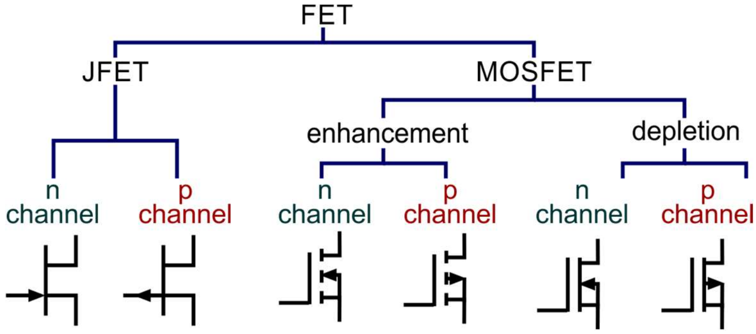


The hardware:

- Bipolar junction transistors (BJT) come in two types, npn or pnp, depending on which impurities are used to 'dope' the single crystal of silicon it is made from.
- Each has two p-n junctions, (n-p p-n) for the npn and (p-n n-p) for the pnp. These are made by diffusing impurities through a photographically-reduced mask into different sections of the silicon.
- There are three regions in the transistor, called collector, base and emitter.
- Various 'leaded' and 'surface-mount' packages, such as TO92 and SOT-23, are used to house the silicon crystal. Some are shown in the photographs at the top of the page. The manufacturer's data sheet may be needed to identify which is which.

Introduction

Field-effect transistors (FETs) have a bigger family than BJTs as the 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 terminal.
- The family has two branches - JFETs and MOSFETs. In both, the gate terminal is insulated from the conducting channel. The mechanism behind this 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 in performance to JFETs in that when the gate voltage, V_{GS},is zero, the drain current is at its maximum. As V_{GS}increases, the 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 possible but production issues mean that p-channel depletion MOSFETs are rare. The most common format is the n-channel enhancement MOSFET.

BJT vs FET:

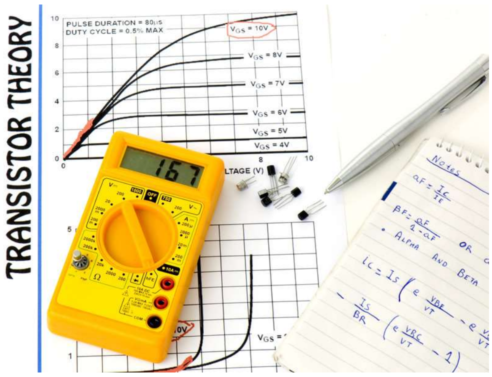
- The FET gate is insulated from the remainder of the device, as described above. As a result, the input current is minute. This leads to FETs being described as voltage-controlled - the drain current is controlled by the gate **voltage**.
- The BJT is a current amplifier - a small base current controls a much larger collector current. It is a **current**-controlled device. The input current flows through a forward-biased p-n junction - a relatively small resistance. The relatively large input current means that the BJT has relatively large input power requirements.

Worksheet 1

Testing BJT transistors

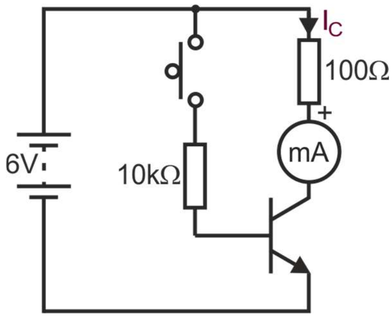
CP4403-1

Transistor amplifiers



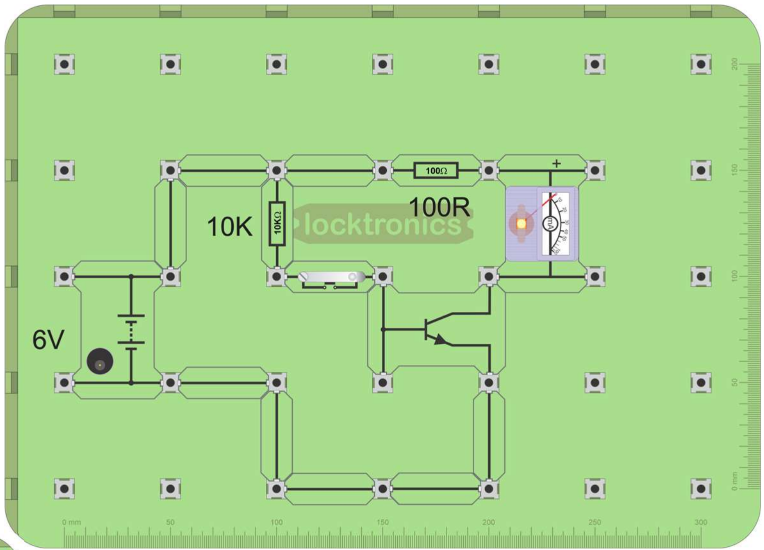
Originally called a ‘transfer resistor’, the transistor is found in almost every electronic circuit, either as a discrete component or within an integrated circuit (IC). ICs contain many hundreds, thousands or even millions of transistors.

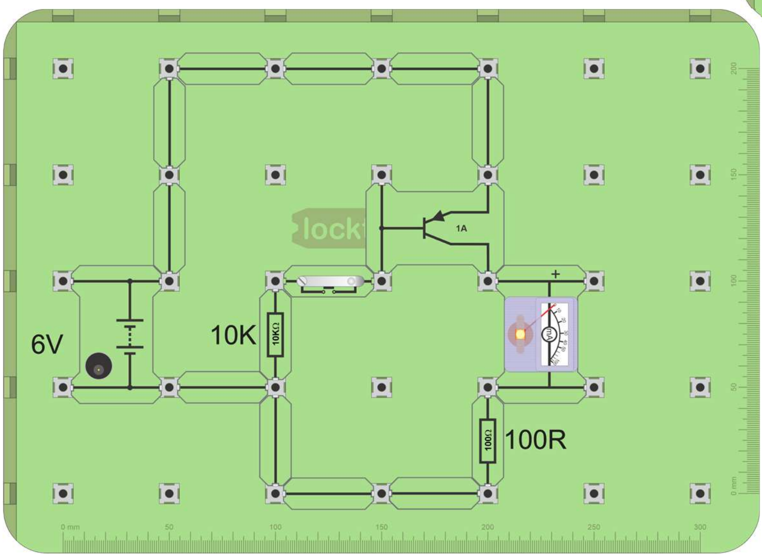
This worksheet shows how to carry out basic checks on BJT (bipolar junction transistors) - both npn and pnp transistors.

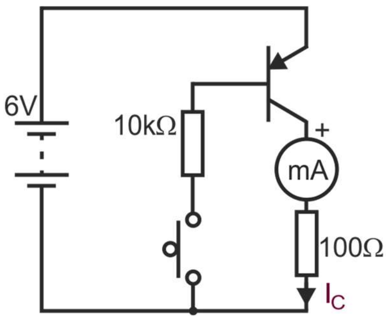


Over to you:

- Build the circuit shown here designed to test npn transistors. A suitable layout is shown.
- Set the DC power supply to output 6V.
- Measure the current flowing in the collector.
- Record the collector current in the table below.
- Press the switch and hold it closed.
- Measure and record the new current.
- Now, build the other circuit, to test the pnp transistor.
- Compare this circuit to the previous one.
- Repeat the same procedure as for the npn transistor.
- Record the results in the table.





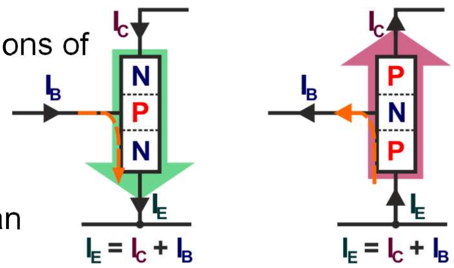


Switch	Base current I_B	Collector
Open	0	
Closed	~0.5mA	

Switch	Base current I_B	Collector
Open	0	
Closed	~0.5mA	

So what?

- Transistors are made from an almost pure silicon crystal, but impurities added to it affect its electrical properties hugely. The impurity concentrations are typically much less than one impurity atom per million silicon atoms The impurities are allowed to diffuse, at high temperature in known concentrations, through a 'mask', producing n-type or p-type regions in the appropriate regions of the crystal depending on the impurity. Adding arsenic or phosphorus creates n-type silicon. Adding boron or gallium creates p-type. N-type silicon contains more free electrons than holes. P-type contains more free holes than electrons.



- Bipolar junction transistors (BJTs) come in two types, npn or pnp. Both contain two p-n junctions, but in a different order, either (n-p p-n), or (p-n n-p).
- The diagrams show the direction of current flow in npn and pnp transistors. You can see why the pnp transistor can be thought of as a mirror-image of the npn device.
- Although it wasn't measured, the base current was around 0.5mA when the transistor was conducting. (When the switch is pressed, there is a voltage drop of ~ 0.7V across the base/ emitter junction of a conducting transistor, leaving ~(6 - 0.7)V across the 10kΩ resistor. This causes a base current of ~ 5.3/10 = ~ 0.5mA.)
- The transistor is a current amplifier. If it is working, the collector current should be at least 50 times bigger than the base current, or at least 25mA. This is the test of whether it is working properly. Check your results against this criterion.

A challenge:

Many multimeters have a transistor-check facility, allowing you to check a transistor quickly. Use one to check some discrete transistors!

For your records:

- Copy the circuit diagrams for the npn and pnp transistor tests.
- Write instructions so that one of your colleagues could carry out the tests.
- Explain to your colleague why the base current is likely to be around 50µA when the switch is pressed.
- Estimate the base current if the 10kΩ resistor were swapped for a 100kΩ resistor.
- Copy the formula for current gain h_{FE}.

Worksheet 2

BJT transfer characteristics

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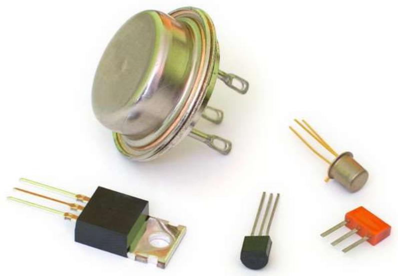
The performance of a transistor can be assessed from graphs that show how base current, collector current and collector-emitter voltage are related.

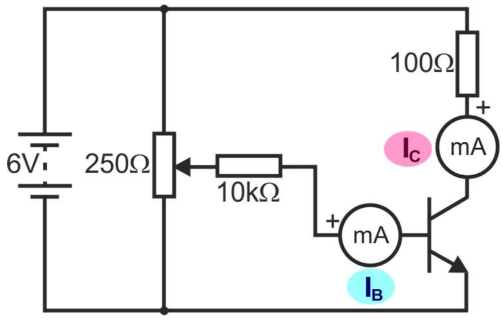
These graphs allow you to predict how a transistor will behave in a particular circuit, and whether or not it is a suitable choice.

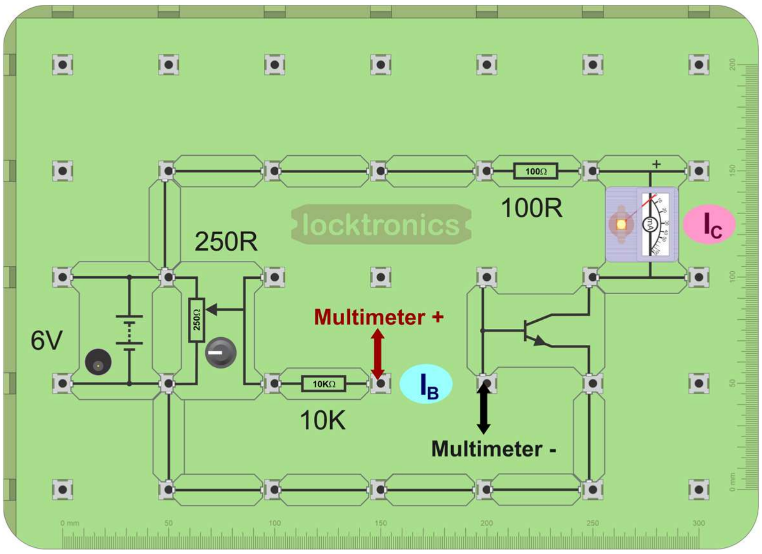
In this worksheet you plot the first of these, known as the **current transfer characteristic, I_C** plotted against **I_B**.



Over to you:

- Build the circuit shown opposite. A suitable layout is shown below it.
- Be careful to connect the 'pot' the right way round!
- Use a multimeter, on the 2mA range, to measure base current, **I_B**. (It is too small to measure accurately on a needle ammeter.)
- Set the DC power supply to output 6V.
- Use the 'pot' to vary base current, **I_B**, shown on the multimeter, from 0 to 0.5mA in 0.1mA steps.
- At each step, measure the collector current,
- **I_C** on the needle ammeter.
- Copy the table and record your results in it.
- Use them to plot a graph of **I_C** against **I_B**, (known as the current transfer characteristic.)
- Suitable scales are given on the template below.
- Assume that it is a straight line graph and draw the best fit through the experimental points.





Worksheet 2

BJT transfer characteristics

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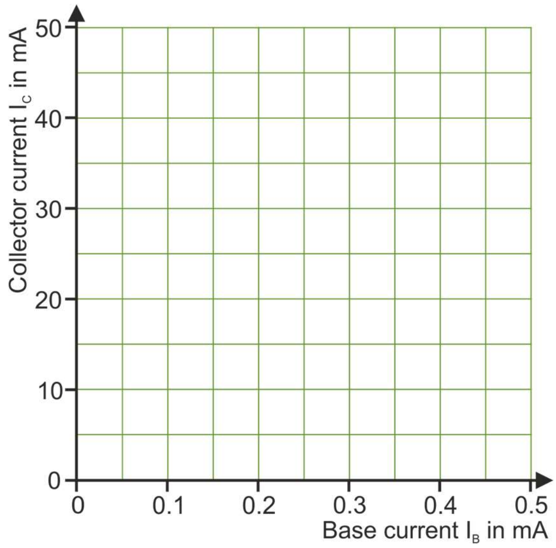
I_B in	I_C in
0	
0.1	
0.2	
0.3	
0.4	
0.5	



w2c

So what?

- Transistors can be categorised by their current gain, called $\mathbf{h_{FE}}$, the ratio of collector current (I_C) to base current (I_B).
- In other words, $h_{FE} = I_C / I_B$
- For example, a BC108 transistor can have a current gain of 300, meaning that the collector current will be 300 times bigger than the base current.
- A base current of 10µA results in a collector current of 300 x 10 µA or 3mA.
- However, a current of 100mA does NOT result in a current of 300 x 100 mA (i.e. 30A!) An effect called saturation limits the maximum collector current. In any case, if the power handling of the transistor is exceeded, it will probably be destroyed!
- The formula implies that a graph of I_C plotted against I_B will be a straight line. This is nearly true, but the current gain does change a little with collector current. One way to obtain the value of current gain is to measure the gradient of the graph you plotted earlier.
- Transistors are mass-produced. The manufacturer will quote typical values for the current gain, but two individual devices may have widely different current gains.

A challenge:

Test different BC108 transistors (or any other type available to you) with a multimeter transistor tester to see the variation in current gain.

Worksheet 2

BJT transfer characteristics

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locktronics® Transistor amplifiers

For your records:

- Copy the circuit diagram for the circuit you set up in this investigation.
- Describe the steps taken to obtain the current transfer characteristic for the transistor.
- Measure the gradient of the graph you plotted to give you an estimate of the current gain of the transistor.
- Identify the transistor used on the transistor carrier. Look for the writing on the transistor body. It may be a ZTX 451. Use the internet to check the manufacturer's value for current gain with the one you obtained.
- Copy the following table and complete it.

Transistor type	**Current gain**	**Base current**	**Collector current in mA**
BC108	500	10mA	
BFY51	60		300
BD437		8mA	500
BC546	200		100
2N3904		100mA	12

w2e

Worksheet 3

BJT output characteristics

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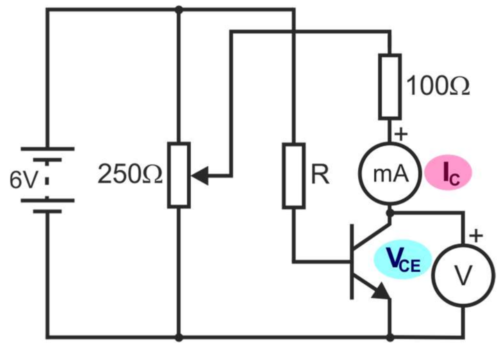
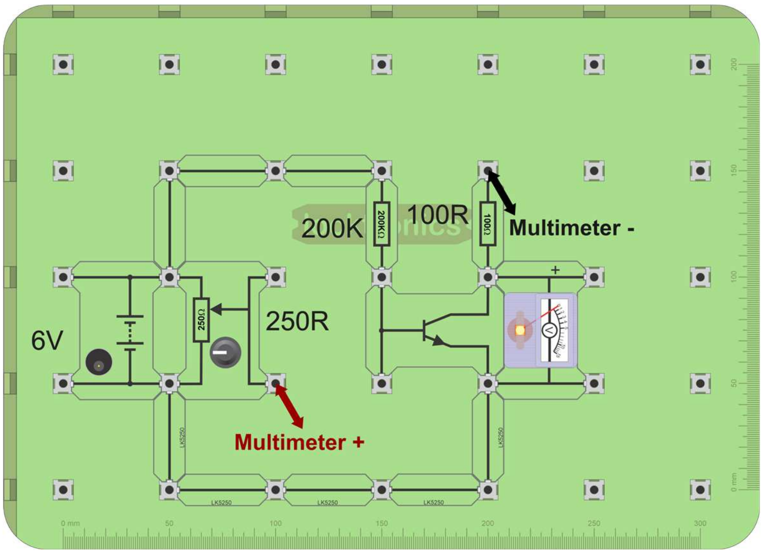
The next characteristic connects the collector current, I_C, with the collector-emitter (output) voltage, V_{CE}.

This allows us to estimate the output resistance of the transistor, which governs how effectively it will pass on a signal to the next subsystem in the circuit.

Over to you:

- Build the circuit shown opposite using a value of 200kΩ for R. The layout shows one way to do this. The multimeter, set up as an ammeter, provides the connection between the ‘pot’ and the 100Ω resistor.
- Set the DC power supply to output 6V.
- Set the multimeter on the 20mA DC range.
- Use the ’pot’ to vary the collector voltage, V_{CE}, shown on the needle voltmeter, from 0V to 5V in 1V steps.
- At each step, measure the collector current, I_C, shown on the multimeter.
- Copy the table that follows and record your results in the centre column.
- Use your results to plot the output characteristic, I_C against V_{CE}. The template opposite suggests suitable scales.
- Now, replace the 200kΩ resistor with a 100kΩ resistor, to give a bigger base current.
- Repeat the process, recording your results in the third column of the table.
- Plot a second output characteristic curve on the same axes.





Worksheet 3

BJT output characteristics

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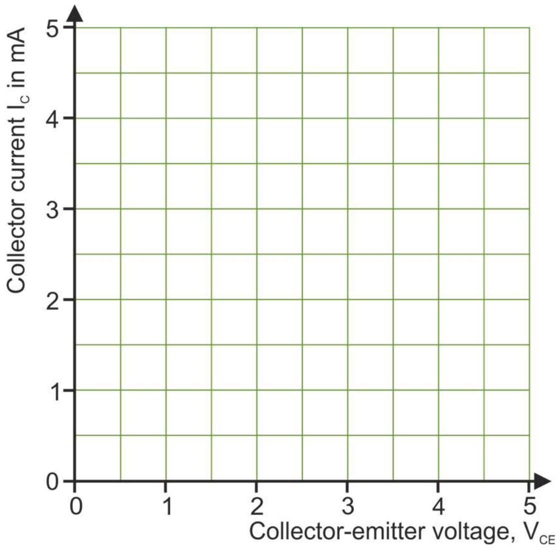
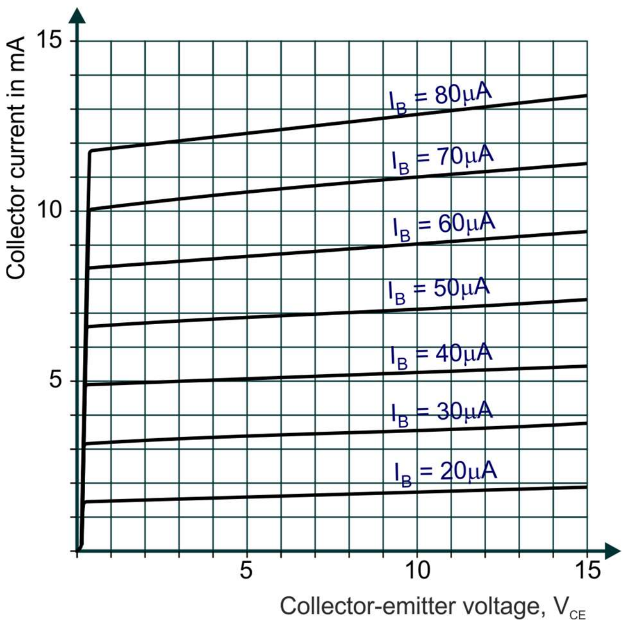
Transistor amplifiers

V_{CE}	I_C in mA	
	R=200k Ω	R=100k Ω
0.0 V		
1.0 V		
2.0 V		
3.0 V		
4.0 V		
5.0 V		



So what?

- Using the 200kΩ resistor, the base current was around 0.3µA. With the 100k Ω resistor, it was twice as big. These small changes in base current had a huge effect on the collector current, I_C, as your graphs show.
- On the other hand, the output voltage, V_{CE}, has very little effect, once the initial 'knee'of the curve is passed. This is surprising!
- In a resistor, the current will double when we double the voltage across it. The transistor is not as simple as that!
- A more detailed investigation, using more values of base current, produces a set of curves like the ones shown in the diagram.
- Once the 'knee' is passed, the behaviour is quite linear, meaning that the output resistance does not change much with output voltage. It can be calculated by taking the inverse of the gradient of the



For your records:

- Copy the circuit diagram for the circuit you set up in this investigation.
- Describe the steps taken to obtain the output characteristic for the transistor.
- Measure the gradient of the linear portion of the two graphs you plotted and hence obtain the output resistance.

Worksheet 4

Transistor as a switch

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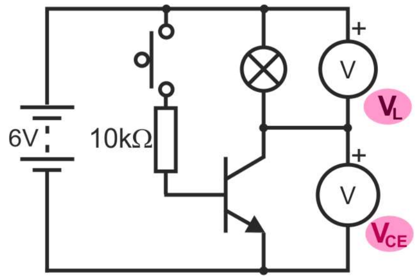
Transistor amplifiers

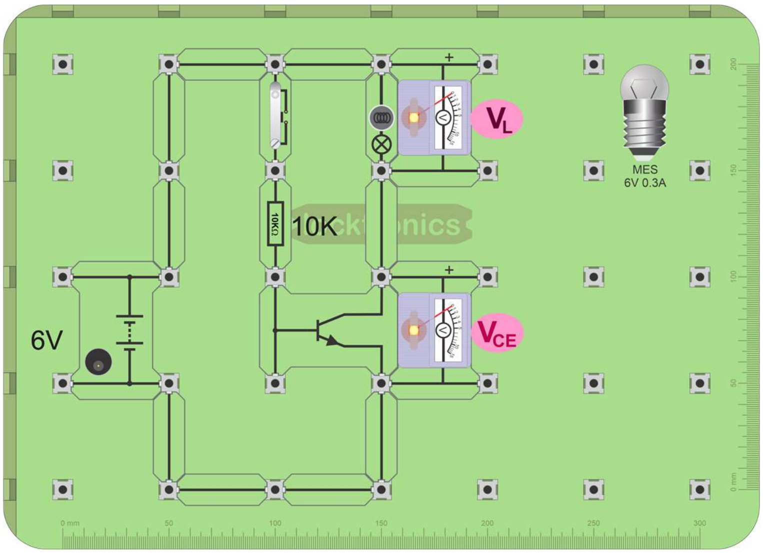
Mechanical switches operate at very low speeds. Transistors, on the other hand, can switch on and off many millions of times faster. There are no moving mechanical parts and so no friction and no 'wear-and-tear'.

In this worksheet you build and test a simple switching circuit.

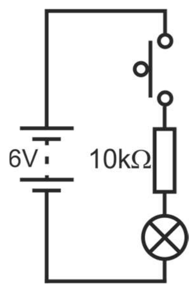
Over to you:

- Build the circuit shown opposite.
- The switch controls the MES lamp. When closed, the small base current produces a much larger collector current through the lamp.
- Set the DC power supply to output 6V.
- Measure voltages V_L, across the lamp and V_{CE}, across the transistor when the switch is open and then when closed.
- Copy the table and record your results in it.
- 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 10kΩ resistor. The lamp then lights perfectly well. The point is that some sensors have a high resistance and will not operate devices like the lamp without the help of a transistor.)
- A switch is a two-state device. It offers huge electrical resistance in one state and around zero in the other.





Switch	V_{CE}	V_L
Off		
On		



Worksheet 4

Transistor as a switch

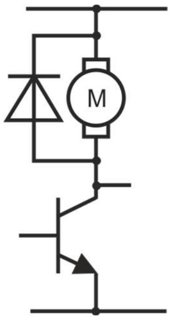
CP4403-4

So what?

- Look at the results for 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 are a voltage divider across the power supply?
- The behaviour is the same as that described earlier for a 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:

- Modify the circuit so that the lamp remains **on** when the switch is open and goes **off** when it is closed. (You will have to change the position of the switch in the circuit).
- 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 creates a strong magnetic field in its coil.
- When the current stops, the magnetic field collapses through the coil and generates a large voltage in the opposite direction, which can damage the transistor.



- The power supply sees the diode in reverse bias. It essentially does nothing when the motor is rotating. The voltage generated by the falling current, however, sees the diode as forward biased. It conducts freely, clamping the voltage drop across it to 0.7V, (or -0.7V) as seen by the transistor). This poses no risk to the transistor.

For your records:

- Copy the circuit diagram for the transistor switch given at the start of the investigation.
- Explain why the transistor can be described as a switch in this arrangement.
- Assuming that the base-emitter voltage is 0.7V when the transistor is on, estimate the base current when the switch is closed in:
  - the lamp circuit;
  - the motor circuit.
- Explain why the base resistor in the motor circuit has a much lower value than that used in the lamp circuit.
- 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.

Worksheet 5

Transistor as an amplifier

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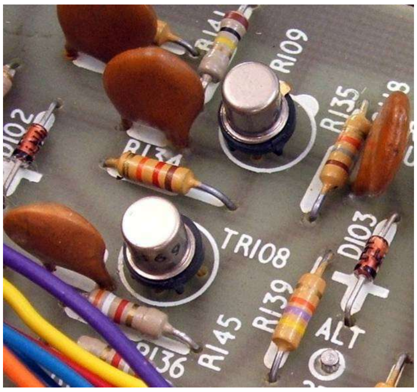
Transistor amplifiers

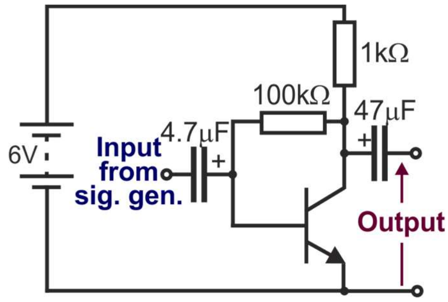


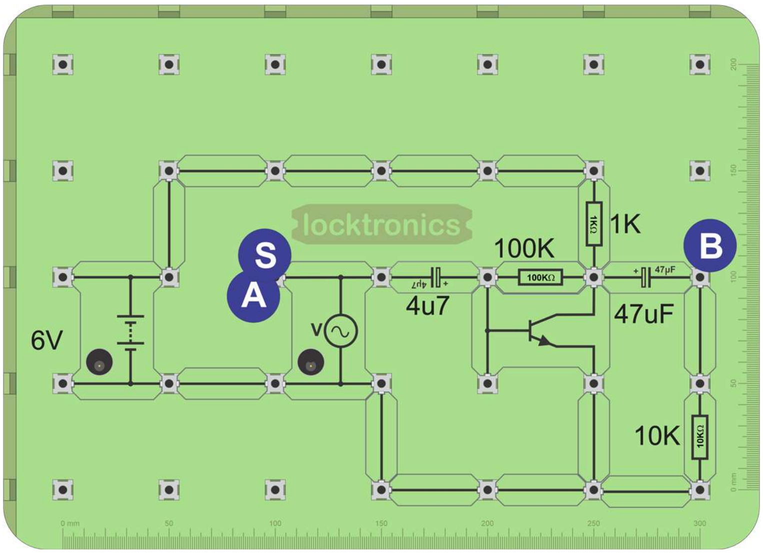
When a bipolar junction transistor is used to amplify audio signals,
we need to provide a DC **bias,** a DC voltage applied to the base so that some collector current will flow even when no signal is present.

This worksheet looks at the operation of a very simple common-emitter amplifier stage that uses this technique.

Over to you:

- Build the circuit shown opposite. Add a 10kΩ resistor as a load for the amplifier.
- Use a multimeter to measure the DC voltages at the collector, base and emitter of the transistor and record your measurements in it.
- Connect the input to a signal generator at point S, with amplitude 50mV at 1kHz.
- Connect a dual-channel oscilloscope to display the input at A and output at B.
- Adjust the oscilloscope controls to display around two cycles of the input and output signals.
- Obtain a trace showing the input and output signals and copy it for your records.
- Measure the amplitude of the input and output signals, and make a note of them.
- Now, increase the input signal amplitude to 100mV. Obtain another trace showing the effect on the output.
- Replace the 10kΩ resistor with a speaker. Use the oscilloscope to observe the effect of the speaker on the output signal.
- Connect the speaker directly to the output of the signal generator. This should convince you that the circuit is amplifying that signal.

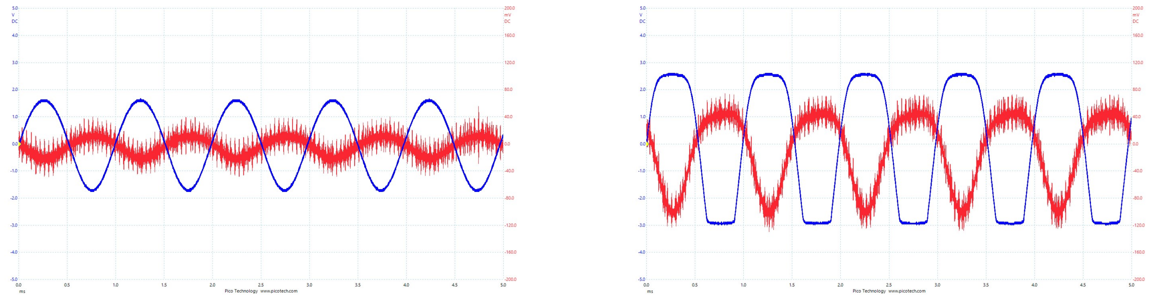




Measurement	Voltage
DC voltage at collector	
DC voltage at base	
DC voltage at emitter	
AC input amplitude	
AC output amplitude	

So what?

The diagrams below show typical oscilloscope traces for this investigation.



Notice that:

- the amplifier inverts the input signal;
- increasing the amplitude of the input signal eventually produces distortion - the output no longer looks like the input;
- because the input signal is very small, the trace (red) contains a lot of electrical noise.

Transistor behaviour:

The 1kΩ resistor and transistor form a voltage divider across the power supply.

When the input voltage **increases**:
- base current **in**creases;
- collector current **in**creases;

When the input voltage **decreases**:
- base current **de**creases;
- collector current **de**creases;

A base current is allowed to flow all the time, through the 1kΩ and 100kΩ resistors, even when no input signal is present (the quiescent state.) This increases the collector current, creating a voltage drop across the 1kΩ resistor. The output voltage, $\mathbf{V_{CE}}$, falls as a result.

The greater the base current, the greater the collector current, the greater the voltage drop across the 1kΩ resistor, and so the lower the output voltage, $\mathbf{V_{CE}}$. The ideal is an output voltage of nearly half of the supply voltage when no signal is present. In that way, the output voltage can rise and fall by similar amounts when a signal is present.

The signal is coupled into and out of the amplifier via capacitors to block any DC components in the signals entering and leaving the amplifier. These could otherwise affect the operation of the amplifier and anything connected to its output.

For your records:

- Copy the circuit diagram for the transistor amplifier.
- Explain what your oscilloscope traces show.
- Use them to estimate the voltage gain before distortion sets in.
- Explain why the output becomes distorted for larger input signal amplitudes.

Worksheet 6

Transformer-coupled amplifier

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Transistor amplifiers

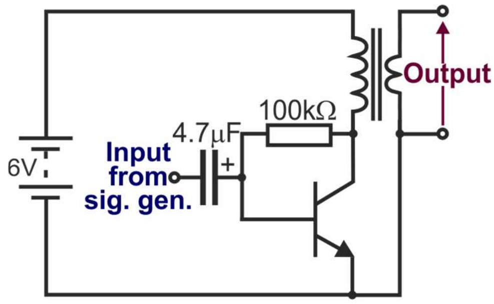
The previous amplifier circuit used a capacitor to couple the signal from the collector to the output.

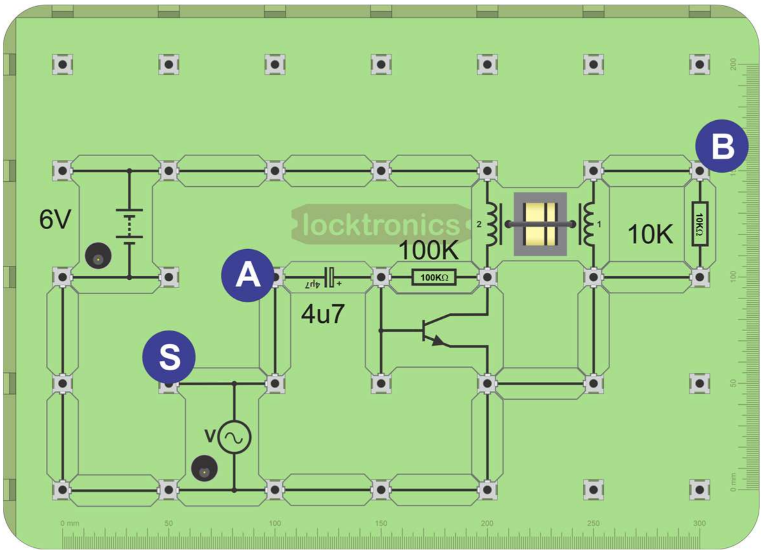
Other methods are used, based on inductors and capacitors, and on transformers. The latter has the advantage of offering accurate matching to a load, such as a speaker, ensuring efficient signal transfer.

This worksheet looks at the operation of a simple transformer-coupled common-emitter amplifier.

Over to you:

- Build the circuit shown opposite.
- A suitable layout follows underneath.
- Again, a 10kΩ resistor acts as a load for the amplifier.
- The 2:1 transformer, connected as a step-down transformer, couples the output to the load.
- Set the DC power supply to output 6V.
- Connect the input to a signal generator, set to output a signal of amplitude 50mV and a frequency of 1kHz.
- Connect a dual-channel oscilloscope to display the input and output signals.
- Adjust the oscilloscope controls to display two cycles or so of the input and output signals.
- Obtain a trace showing the two signals and copy it for your records.
- Copy the table ready to record your measurements.
- Measure the amplitudes of the input and output signals, and record them in the table.
- Use them to estimate the voltage gain of the amplifier and enter it in the table.
- Now, increase the input signal amplitude to 100mV. Obtain a new trace showing the effect on the output.

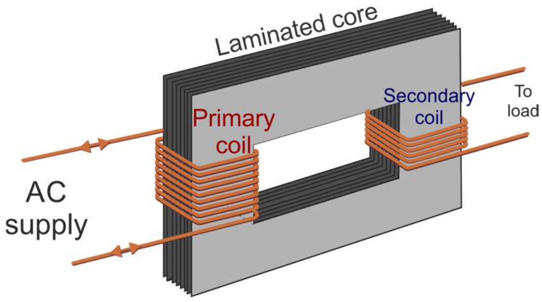




Measurement	Voltage
AC input amplitude	
AC output amplitude	
Voltage gain =	

So what?

- In the capacitor-coupled amplifier studied earlier, the collector current flowed through the 1k Ω resistor in series with it. This generates waste heat. The aim of transformer-coupling is to reduce that energy loss.
- The diagram that follows illustrates the main features of a transformer.



- It consists of two coils wound around a magnetic core, laminated to reduce stray heating effects. The coils are electrically insulated from each other and from the core. Alternating current flowing in one coil, called the primary, produces an alternating (i.e. moving) magnetic field. This links with the other coil, called the secondary, and induces an alternating current in it. DC currents do not produce the same effect as there is no moving magnetic field.
- In a step-down transformer, the primary coil, the one supplied with AC power, has more turns of wire than the secondary, the one that generates the transformer output voltage. This transformer has a turns ratio of 2:1, meaning that one coil has twice as many turns as the other. The primary will be the ‘2’ coil, and the secondary the ‘1’ coil.
- As a result, the load is isolated from any DC currents flowing in the transistor, but receives the AC signal, via the transformer.
- For maximum efficiency, the transformer is chosen so that the output impedance of the transformer is equal to the load impedance. This is an example of the maximum power transfer theorem.

A challenge:

Investigate what happens if the transformer is reversed, to act in step-up rather than step-down mode.

For your records:

- Copy the circuit diagram for the amplifier.
- Explain what your oscilloscope traces show.
- Use them to estimate the voltage gain when the input voltage is 50mV.
- Using resources such as the internet or text-books, distinguish between ‘step-up’ and ‘step-down’ transformers.

Worksheet 7

Stabilised common-emitter amplifier

CP4403-7

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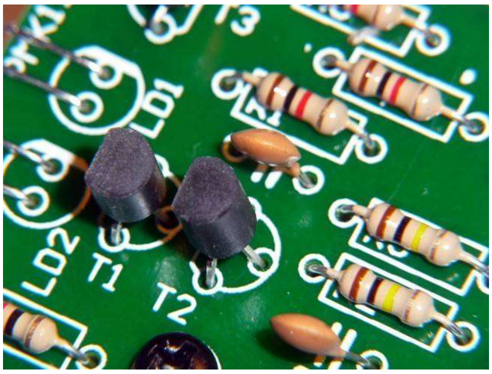
Transistor amplifiers

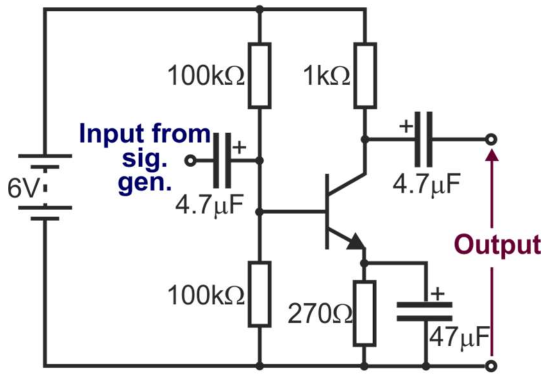
The simple common-emitter can be improved by adding DC negative feedback to stabilize it and compensate for variations in factors like transistor parameters, component tolerances and temperature changes.

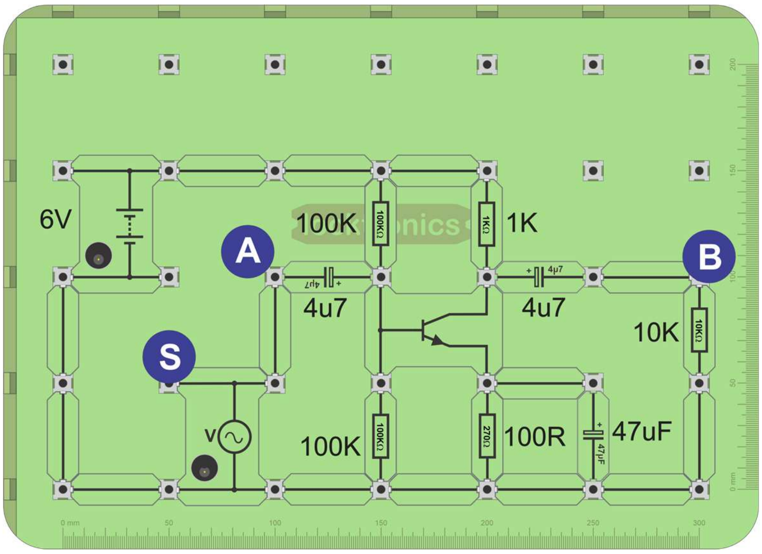
This worksheet looks at the operation of a stabilised common-emitter amplifier.



Over to you:

- Build the circuit shown opposite.
- A suitable layout is given underneath, including a 10kΩ resistor, added as a load for the amplifier, once more.
- Set the DC power supply to 6V.
- Use a multimeter to measure the DC voltages at the collector, base and emitter of the transistor.
- Copy the table and record your measurements in it.
- Connect the input to a signal generator, set to generate a signal of amplitude 50mV and frequency 1kHz.
- Connect a dual-channel oscilloscope to display the input and output signals.
- Connect the ground terminals of the signal generator and oscilloscope to 0V.
- Adjust the oscilloscope controls to display two cycles or so of the input and output signals.
- Obtain a trace showing the signals and copy it for your records.
- Measure the amplitudes of the input and output signals, and record them in the table.





Measurement	Voltage
DC voltage at collector	
DC voltage at base	
DC voltage at emitter	
AC input amplitude	
AC output amplitude	

Worksheet 7

Stabilised common-emitter amplifier

CP4403-7

So what?

The amplifier studied in worksheet 6 used one form of negative feedback to stabilise the amplifier, by means of the resistor connecting base and collector terminals. The control mechanism was described in the 'So what' section of the worksheet.

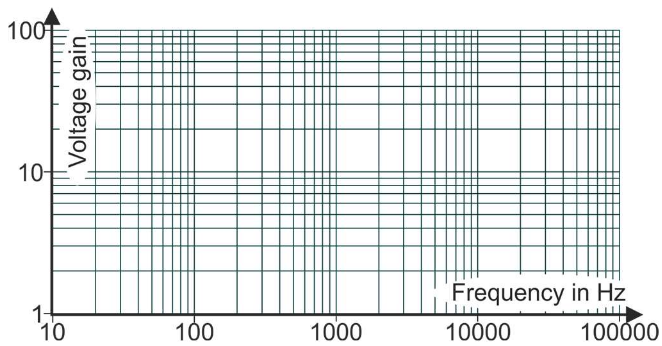
In this circuit, the negative feedback is provided in a different way, using an emitter resistor. This removes the need for a resistor between base and collector. However, there still needs to be a base current in the quiescent (no signal) state. Otherwise the transistor would ignore any AC voltage less than 0.7V (i.e. over half of it!) Here, the base terminal is set at a voltage determined by the voltage divider formed by the two 100kΩ resistors - no feedback involved!

Negative feedback, provided in this circuit via the 270Ω emitter resistor, returns a signal which opposes changes at the output. If any temperature or power supply changes etc. cause the DC collector current to rise, the voltage across the 270Ω emitter resistor also rises. As a result, the voltage drop across the base-emitter junction falls, reducing the base current and, in turn, reducing the collector current - negative feedback!

A side-effect is to reduce the voltage gain of the amplifier. The emitter resistor bypass capacitor, the 47µF capacitor, does not affect **DC** currents - they see it as a gap in the circuit. However, **AC** signals can flow through this capacitor, instead of the emitter resistor.
As a result, the **AC** voltage gain is not affected as much.

A challenge:

- Investigate what happens to voltage gain when the input signal frequency changes.
- Vary the frequency over the range 50 Hz to 100 kHz and measure the voltage gain at suitable intervals.
- Use your results to plot a frequency response graph, showing voltage gain plotted against frequency.
- A 'log-log' grid is best as it allows you to cover very large ranges of frequency.



The diagram above shows a 'log-log' template. If necessary, ask your tutor for help!

For your records:

- Describe the function of the voltage divider connected to the base of the transistor.
- How does the emitter resistor provide negative feedback?
- Explain how the emitter resistor bypass capacitor affects voltage gain.
- Using resources such as the internet or text-books, explain what is meant by 'negative feedback' and describe its effects in applications like the current one.

Worksheet 8

Emitter follower behaviour

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Transistor amplifiers

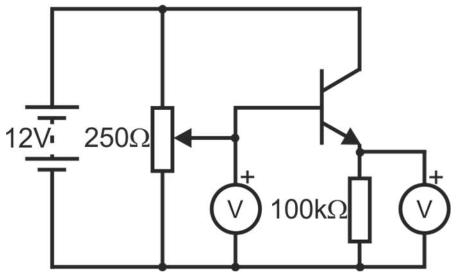
The circuits so far use the 'common-emitter' configuration, where the emitter is part of both the input and output circuits. Usually designed to produce a large output voltage signal from a small input signal, they are known as 'small signal amplifiers'.

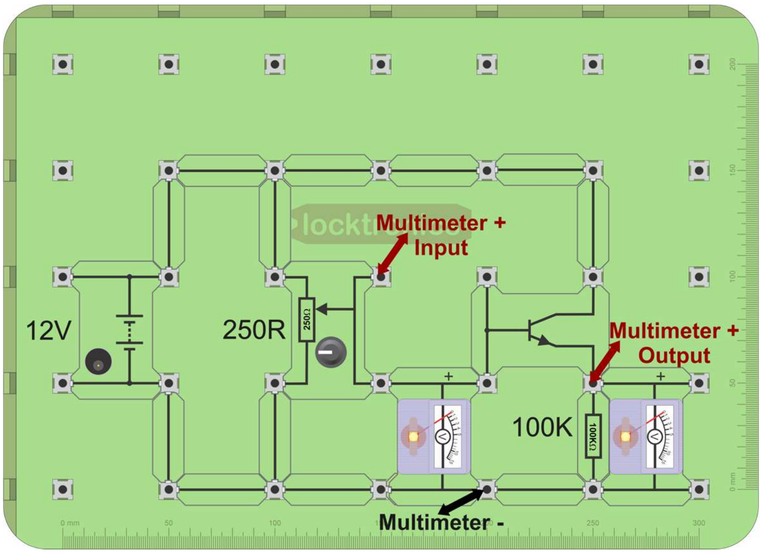
This worksheet looks at a different configuration - 'common-collector' where the collector is connected directly to the positive power supply rail, with the load connected between emitter and 0V rail.

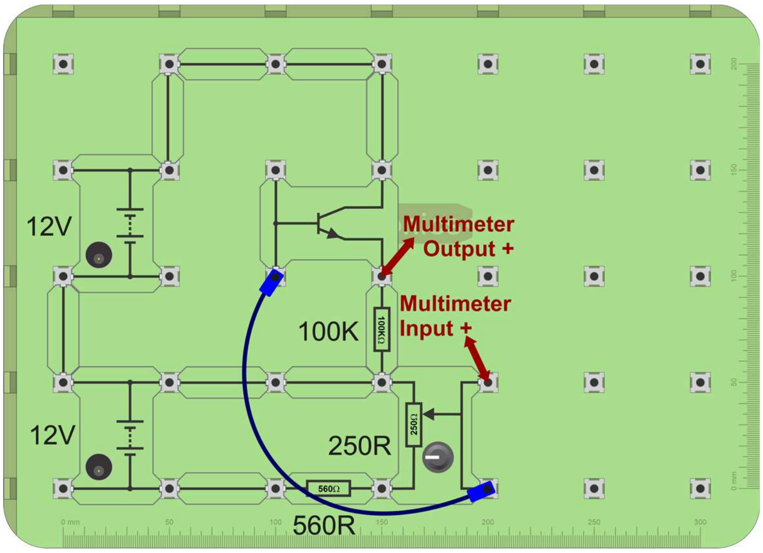
The emitter follower delivers both high signal voltage and current to a load such as a speaker. It usually uses power transistors like the one shown in

Over to you:

- Build the circuit shown opposite.
- Use the 'pot' to vary the input voltage. Watch the voltmeters as you do so. The output voltage 'follows' the input - hence the name of this circuit!
- Next use a multimeter, connected as shown, to make more accurate measurements.
- Use the 'pot' to set the input voltage to 0V.
- Measure the corresponding output voltage.
- Copy the table and record your measurements in it.
- Set the input voltage to the other values in the table. Measure and record the output voltages produced.
- Modify the circuit to that shown in the second layout. This allows you to apply negative voltages.
- The 560Ω resistor prevents excessive negative input voltages.
- As before, set the input voltage to the values in the table. Measure and record the output voltages produced.







Worksheet 8

Emitter follower behaviour

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Transistor amplifiers

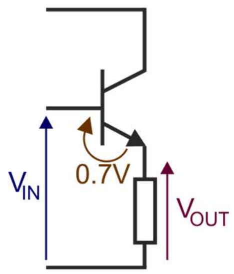
Input voltage V_{IN}	Output voltage V_{OUT}
0	
1.0	
2.0	
3.0	
4.0	
5.0	

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

So what?

- 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 resistor, as output voltage V_{OUT}.
- Hence, the emitter follower relationship:

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



Voltage gain:

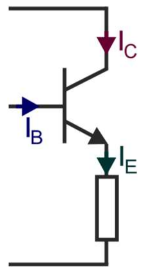
$$\text{Voltage gain} = V_{OUT} / V_{IN} = \sim 1$$

Current gain:

Output current through load = emitter current I_E

Input current = I_B

Current gain = I_E / I_B



From Kirchhoff's current law:

$$I_E = I_C + I_B$$

and $I_C >> I_B$

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

A challenge:

- Carry out the same investigation for the pnp transistor. Essentially, it means reversing all the power supply connections.
- Let your instructor see your circuit before switching it on.

For your records:

- Copy the circuit diagram for the emitter follower.
- Use your results to plot a graph of V_{OUT} against V_{IN} (i.e. the voltage transfer characteristics) for the emitter follower.
- Copy the expressions given above for the emitter follower relationship, its voltage gain, and its current gain.
- Write an explanation for one of your fellow students to show that emitter follower has an overall power gain (= voltage gain x current gain).

Worksheet 9

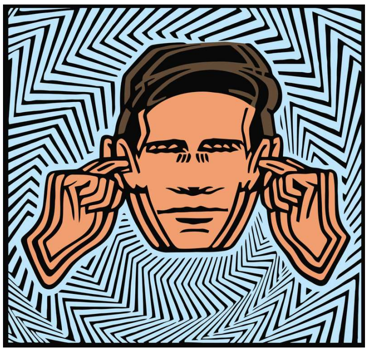
Emitter follower - AC behaviour

CP4403-9

The aim of amplifier systems is to reproduce recorded sounds faithfully, but louder **and with no distortion!**

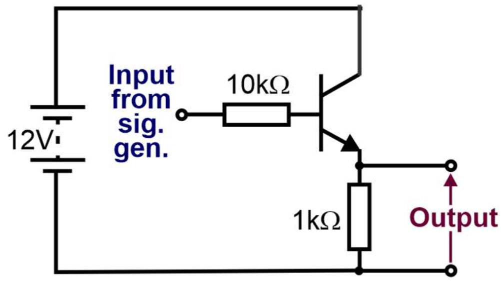
The sounds are converted into AC electrical signals, so the system must be able to amplify these AC signals faithfully.

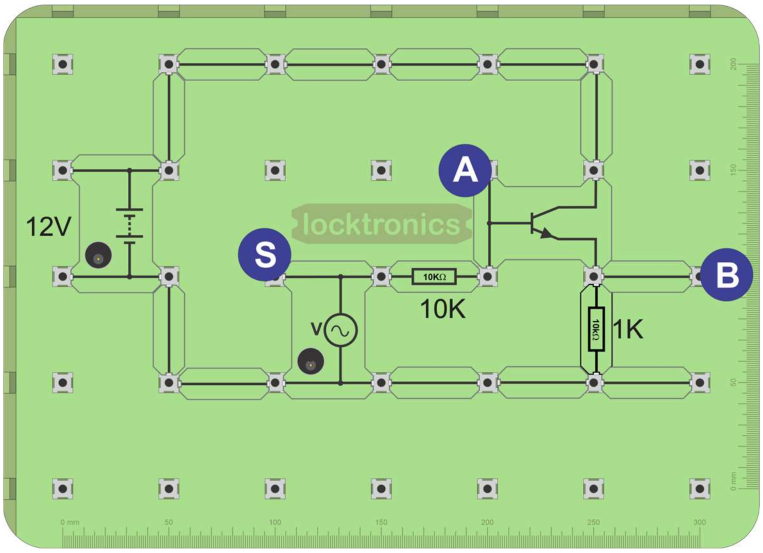
This worksheet looks at the way in which the simple emitter follower, studied in the previous worksheet, handles AC signals.



Over to you:

- Build the circuit shown opposite.
- The diagram includes two capacitors to block any DC components in the signals, so that they do not affect the operation of the emitter follower or the circuits it is connected to.
- A suitable layout is given underneath.
- Set the DC power supply to 12V.
- Connect the input to a signal generator, at S, set to output a signal of amplitude 2V and frequency 1kHz.
- Connect a dual-channel oscilloscope to display the input and output signals at A and B.
- Set the 'Voltage sensitivity' on each channel to +/- 5V.
- Connect the ground terminals of the signal generator and oscilloscope to 0V.
- Adjust the oscilloscope controls to display a few cycles of the input and output signals.
- Obtain a trace showing the signals and copy it for your records.





Worksheet 9

Emitter follower - AC behaviour

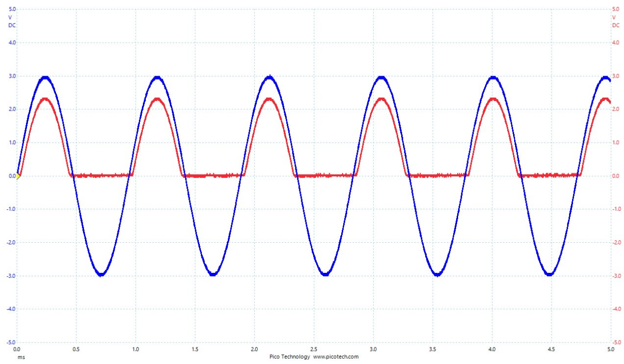
CP4403-9

locktronics
Transistor amplifiers

So what?

A problem:

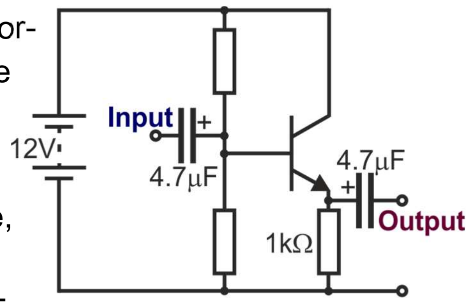
The output signal is distorted! It is not a true copy of the input signal - half of it is missing! In the light of the results of the previous worksheet, this is not surprising. The basic emitter follower handles only positive signals.



The diagram opposite shows a typical trace of the input (blue) and output (red) signals.

Challenges:

- Replace the 1kΩ resistor with a speaker.
- Compare the sound produced with that when the speaker is connected directly to the output of the signal generator. You should hear the distortion!
- One solution is to create a steady DC bias for the emitter.
- Experiment with the arrangement shown to try to reduce distortion by making the transistor conduct throughout the full cycle of the signal.



Design hints:

- Choose an emitter voltage of about half of the supply voltage, i.e. ~6V, to allow the output voltage to swing ~6V either way.
- Calculate the collector current (roughly the emitter current,) = 6V/1kΩ = 6mA.
- Hence estimate the base current (I_C / h_{FE}) so around 6/100 mA (0.06mA) here.
- Estimate the base voltage (= emitter voltage + 0.7V.)
- Assume a current down the resistor chain of 10 x base current (so ~0.6mA)
- Current through top resistor is greater than that through the bottom one by the base current. Choose appropriate values for the resistors.

For your records:

- Copy the circuit diagram for the emitter follower, modified to accept and output AC signals.
- Explain the purpose of the two capacitors.
- Explain why the circuit creates distortion.
- Draw the circuit diagram for the modification given in the second challenge.
- Explain why this modification should reduce the distortion.

Worksheet 10

Push-pull follower

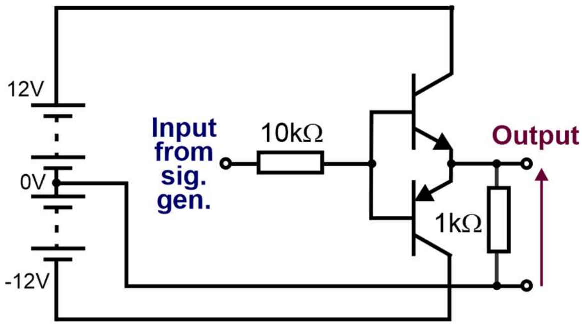
CP4403-10

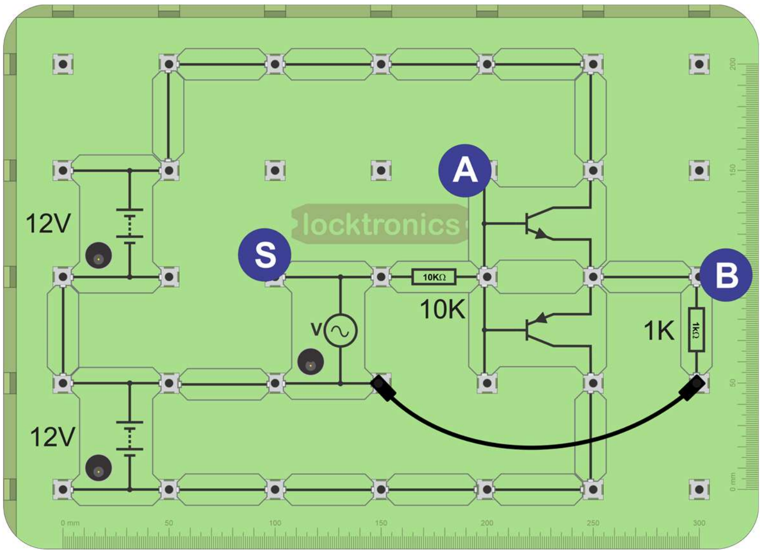
The emitter follower has a serious limitation as a power amplifier for AC signals - it only responds to half of the AC waveform. The solution is to add a steady DC voltage to the base so that the transistor is conducting all the time. The previous worksheet looked at using a voltage divider of two resistors to do this. They pass current all the time, heat up and waste energy.

This worksheet looks at a different solution which avoids this.

Over to you:

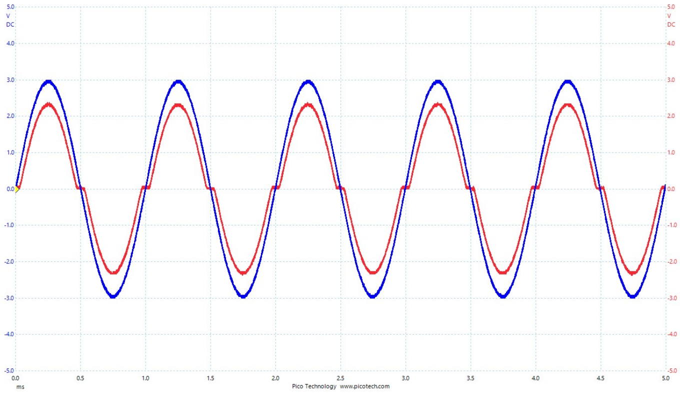
- Build the circuit shown opposite. The diagram includes two capacitors to block any DC components in the signals.
- A suitable layout is given underneath, without the two DC-blocking capacitors. When needed, they can easily be added to the layout. It uses a 1kΩ resistor as a load.
- The circuit uses a split +12/0/-12V power supply.
- Connect the input to a signal generator, set to generate a signal of amplitude 3V and frequency 1kHz.
- Connect a dual-channel oscilloscope to display the input and output signals.
- Set the 'Voltage sensitivity' on each channel to +/- 5V.
- Connect the ground terminals of the signal generator and oscilloscope to 0V.
- Adjust the oscilloscope controls to display a few cycles of the input and output signals.
- Obtain a trace showing the signals and save it for your records.
- Next, reduce the amplitude of the signal to 1V. The trace should show any distortion more clearly.
- Save this second trace for your records.





So what?

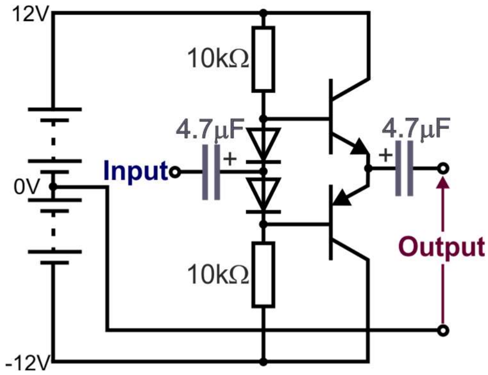
The diagram shows typical signals for this circuit. The input is shown in blue and the output in red.



Much of the distortion has gone - there is a negative portion to the output signal as well as a positive. The main distortion occurs in between the two, where the input signal is close to 0V. It appears as a 'shoulder' in the output signal. It is called cross-over distortion and occurs when the input is too small to turn on either transistor. In other words, it occurs for input voltages between +0.7V and -0.7V approximately.

Challenges:

- Once again, replace the 1kΩ resistor with a speaker. There is still some distortion - it sounds harsher than when the speaker is connected directly to the signal generator.
- The circuit shown can be used to eliminate cross-over distortion. The two diodes are conducting and so have a voltage drop of 0.7V across them.
- As a result, the base of the npn transistor sits at 0.7V above the signal voltage. When the signal voltage is 0V, the npn transistor base is at 0.7V and conducts.
- Equally, it conducts for any voltage greater than 0V.
- Similarly, the base of the pnp transistor sits at 0.7V below the signal voltage, and so conducts at all voltages below zero.



For your records:

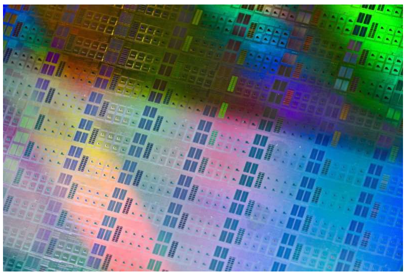
- Copy the circuit diagram for the push-pull follower, with the DC blocking capacitors in place.
- Explain why the circuit creates cross-over distortion.
- Draw the circuit diagram for the modification given in the second challenge.
- Explain why this modification should reduce distortion.

Worksheet 11

FET transfer characteristics

CP4403-10

Transistor amplifiers



Made from the same silicon wafer, using similar techniques, the FET (field-effect transistor) has equivalent applications to the BJT but uses different principles.

The BJT family has only two members, npn and pnp. The FET family tree is much bigger.

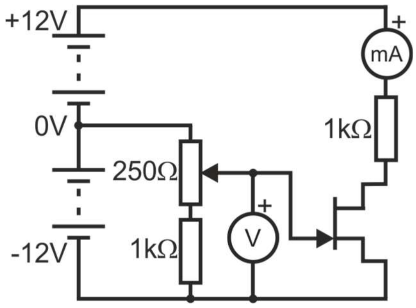
In this worksheet, the behaviour of JFET (junction FET) and MOSFET (metal-oxide semiconductor FET) devices is studied.

Over to you:

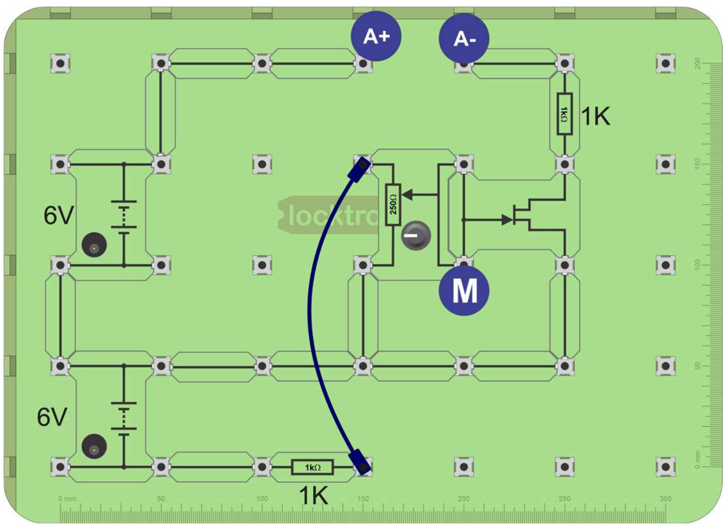
- The first part focuses on the JFET, operating in depletion mode. Build the circuit shown opposite. The 1kΩ resistor connected to the 'pot' reduces the range of voltages available, but increases the ease of adjustment.
- Use a multimeter to measure drain current, I_D (up to 5mA).
- Use a second multimeter to measure gate-source voltage (V_{GS}) (from 0V to -5V).
- Use the 'pot' to set the input voltage (V_{GS}) to 0V, and measure the corresponding drain current, I_D.
- Copy the table and record your measurements in it.
- Set the input voltage to the other values in the table. Measure and record the drain currents produced.

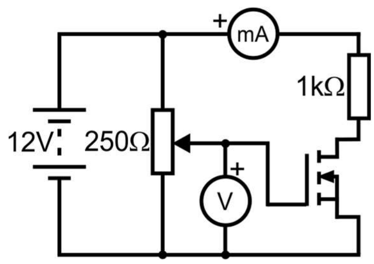
A challenge:

- Now carry out the exercise for the MOSFET, which operates in enhancement mode.
- The circuit diagram is given, but you should design your own layout. Use the 'pot' to input voltages from 0V to +5.0V and measure the drain current each time.
- Create a suitable table in which to record your results.



Input V_{GS}	**Output I_D**
0	
-0.4	
-0.6	
-0.8	
-1.0	
-1.2	
-1.4	





Worksheet 11

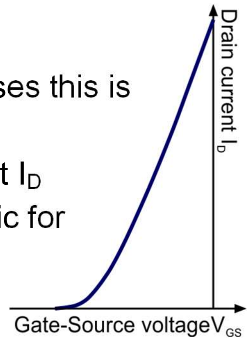
FET transfer characteristics

CP4403-10

So what?

JFET:

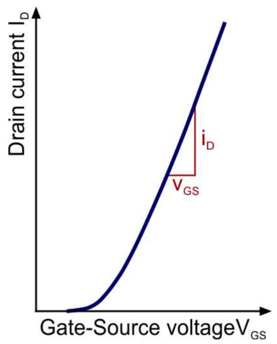
- The drain current is at a maximum when the gate-source voltage is zero.
- As V_{GS} becomes more negative, drain current decreases.
- Eventually the drain current falls to zero. The gate-source voltage that causes this is known as the pinch-off voltage.
- Use your measurements from the first circuit to plot a graph of drain current I_D against gate-source voltage V_{GS}. This is known as the transfer characteristic for the JFET. Use the graph opposite as a guide for drawing the curve.



MOSFET:

- No drain current flows until V_{GS} reaches a threshold value.
- Then, as V_{GS} increases, drain current increases almost linearly.
- Use your measurements to plot a graph of drain current I_D against gate-source voltage V_{GS}, the transfer characteristic for the MOSFET. Use the graph opposite as a guide for drawing the curve.
- The gradient of the graph is called the transconductance, g_m:

$$g_m = \frac{\text{change in drain current}}{\text{change in gate-source voltage}} = \Delta I_D / \Delta V_{GS}$$



A challenge:

- Design a circuit to test conduction in the MOSFET when the gate-source voltage is negative (up to -5V).
- **Let your instructor see your circuit before switching it on.**

  DO **NOT** USE A POSITIVE VOLTAGE ON THE GATE-SOURCE TERMINAL OF THE ***JFET***. YOU MAY DESTROY IT!

For your records:

- Explain what is meant by the term 'transfer characteristic' for a FET.
- Write an explanation of less than 100 words, for a fellow student, on the differences in the way a depletion-mode JFET and an enhancement-mode MOSFET are used in a circuit.
- Draw the circuit diagram for the investigation into the MOSFET transfer characteristic and write a simple list of instructions for a fellow student, including how to process the results.
- Copy and complete the following:
- When a MOSFET has a transconductance of 30mS, the drain current will be ………. for a gate-source voltage of 3.0V.

Worksheet 12

FET output characteristics

CP4403-10

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Transistor amplifiers

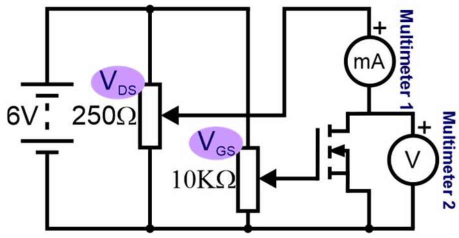
A device's output characteristics determine the way it interfaces with the following subsystem.

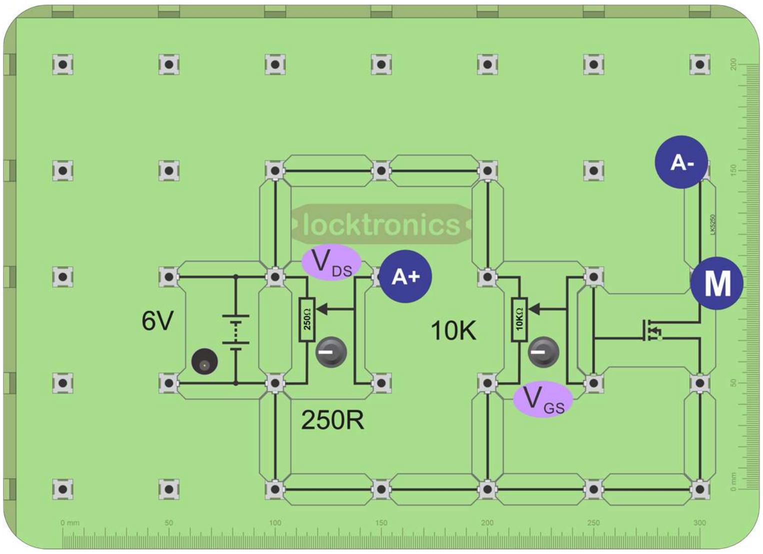
To deliver power efficiently to the next stage, output impedance ('AC resistance') should be low.
To deliver a voltage signal to the next stage, it should be high.

This worksheet shows how to measure the MOSFET's output characteristics.

Over to you:

- Build the circuit shown opposite.
- The layout shows one way to do this.
- (Be careful to connect the two 'pots' correctly!)
- The multimeter, set up as an ammeter, connects the 'pot' and the MOSFET.
- Set the DC power supply to output 6V.
- Set multimeter 1 on the 200mA DC range and multimeter 2 on the 5V DC range.
- Use the 'V_{GS}' 'pot' to set the gate voltage to 2.2V.
- Use the 'V_{DS}' 'pot' to vary the drain voltage from 0V to 1V in 0.1V steps.
- At each step, measure the drain current, I_D, on multimeter 1.
- Copy the table and record your results in it.
- Use them to plot the output characteristic, I_D against V_{DS}.
- Now, set the gate voltage 'V_{GS}' to 2.4V.
- Repeat the process, recording your results in the table.
- Plot a second output characteristic curve on the same axes.



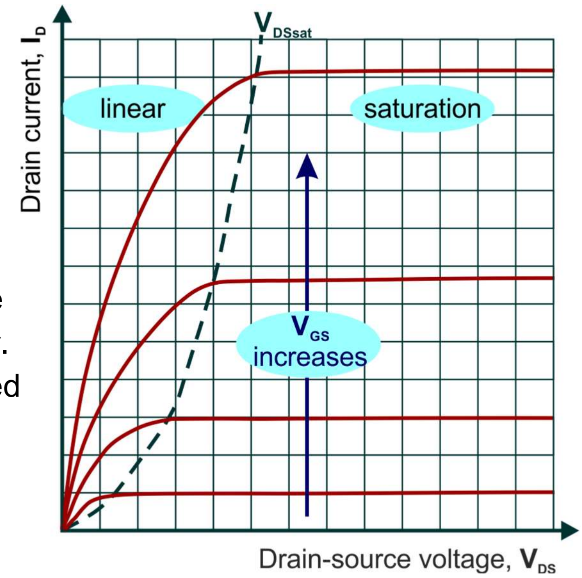


V_{DS}	V_{GS} = 2.2V	V_{GS} = 2.4V
	I_D in mA	I_D in mA
0.0 V		
0.1 V		
0.2 V		
0.3 V		
0.4 V		
0.5 V		
0.6V		
0.7V		
0.8V		
0.9V		
1.0V		

So what?

Your graphs should resemble those opposite. The traces show the effect of four different values of V_{GS}, the gate-source voltage.

There are two distinct regions for each curve:



- 'linear' (or 'ohmic') region:
  - For small values of drain-source voltage, (V_{DS}), the drain current, I_D, increases almost linearly with V_{DS};
  - The traces are nearly straight lines through the origin - what you would expect for a resistor. However, it is a resistor with a value determined by the gate-source voltage, V_{GS}. It is known as the 'On' state resistance of the MOSFET, $R_{DS(on)}$.
  - $R_{DS(on)}$ reduces as V_{GS} increases. It is usual to quote the values of V_{GS} and I_D at which $R_{DS(on)}$ is measured. For example, the RFP30N06LE MOSFET, used in the Locktronics carrier, has a $R_{DS(on)}$ value of 0.05Ω when V_{GS} = 5V and I_D = 30A.
- 'saturation' region:
  - Changes in V_{DS} have little effect on I_D.
  - Drain current is insensitive to changes in V_{DS}, but is hugely affected by V_{GS}.

Below a threshold gate voltage, $V_{GS(th)}$, no drain current flows.
For the RFP30N06LE $V_{GS(th)}$ is between 1V and 2V.

The boundary between the 'linear' and 'saturation' regions is called the 'pinch-off region'.

For your records:

- Copy the circuit diagram for the circuit you set up in this investigation.
- Describe the steps taken to obtain the MOSFET output characteristic.
- Measure the gradient of the two graphs you plotted to obtain estimates of $R_{DS(on)}$.
- Copy and complete the following:
- A 2N7000 MOSFET has a value of $r_{DS(on)}$ of 5Ω. A drain current I_D of 200mA will dissipate ……….mW in the device.

Worksheet 13

MOSFET switch

CP4403-10

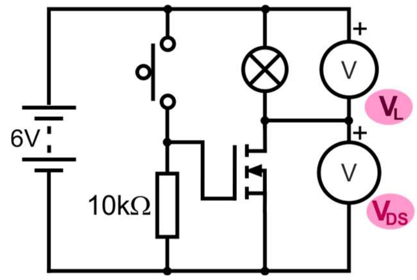
A BJT switch exists in either the ‘off’ state, where all the supply voltage sits across the transistor, or the ‘on’ state, where the voltage across the transistor is almost zero.

The reason for this is the dependence of collector-emitter resistance on the base current - the BJT is a current-controlled device.

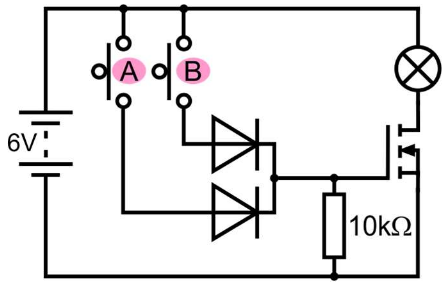
That can be the problem - some subsystems are not able to deliver sufficient current to switch the BJT on. This worksheet looks at the comparable behaviour of a MOSFET switch.

Over to you:

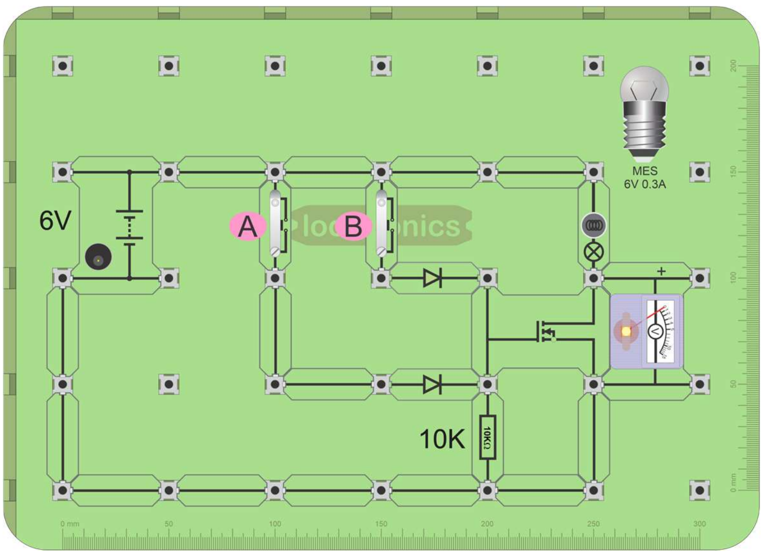
- Build the circuit shown opposite.
- Set the DC power supply to output 6V.
- Measure voltages V_L, across the lamp and V_{DS}, across the MOSFET when the switch is open and then when closed.
- Copy the table and record your results in it.
- The next circuit illustrates the use of a MOSFET as a logic gate.
- Build the circuit shown. A possible layout is given below. A voltmeter has been added to indicate the output state of the MOSFET.
- The task is to identify the logic function.
- Press switches **A** and **B** in all four possiblecombinations. These are listed in the table.
- For each combination, measure the output voltage across the MOSFET.
- Copy the following table and complete it with your results:



Switch	V_{DS}	V_L
Off		
On		



Switch **A**	Switch **B**	**MOSFET**
Open (off)	Open (off)	
Open (off)	Closed (on)	
Closed (on)	Open (off)	
Closed (on)	Closed (on)	



Worksheet 13

MOSFET switch

So what?

A logic *function* is one way of manipulating digital signals. A logic *gate* is a device that will carry out a particular logic function. There are not many logic functions. For example, an AND gate outputs a logic 1 signal only when all its inputs sit at logic 1. MOSFETs are widely used inside digital ICs to perform logic functions.

- Remember the rules for digital logic signals:
  - a low voltage, close to 0V, represents logic 0;
  - a high voltage, close to 6V, represents logic 1;
  - a switch delivers a logic 1 signal when pressed.
- The next step is to convert your measurements to logic signals, and complete the truth-table for the logic function.
- Copy the table and use your results in it to complete the logic state of the output.

Input **A**	Input **B**	Output
0	0	
0	1	
1	0	
1	1	

Circuit features:

- The diodes isolate the two input devices (switches.) For example, when switch **A** is pressed, the lower diode is forward biased and conducts. As a result, the MOSFET gate terminal sits at a positive voltage. This reverse biases the upper diode, isolating switch **B** from the signal from switch **A**.
- The insulated gate terminal and source acts as a small capacitor, usually only a few nano-Farads, but this can become charged and affect the performance. The 10kΩ resistor discharges this capacitor.

A challenge:

Modify the second circuit so that it acts as an 'AND' gate.

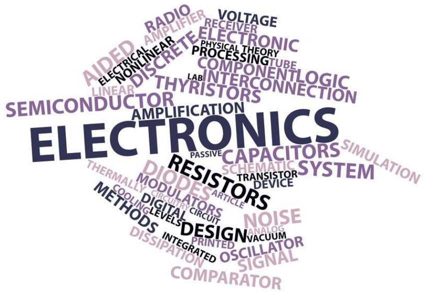
For your records:

- Copy the circuit diagram for the MOSFET switch.
- Write a brief explanation (no more than three sentences,) for a fellow student on why the circuit can be described as a switch.
- Use the datasheet for the `RFP30N06LE` to find the following information for this MOSFET:
- 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.

Worksheet 14

MOSFET applications

CP4403-10

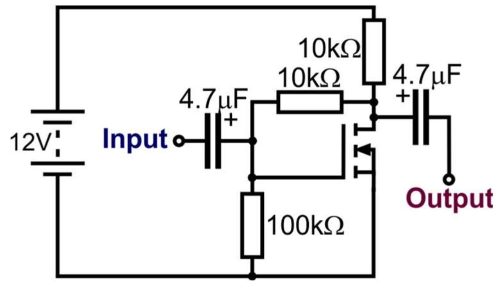


Depending on the application, MOSFETs can offer significant advantages over BJTs, including higher input impedance, smaller power loss - the effect of $R_{DS(ON)}$ is usually smaller than that of the BJT forward voltage drop V_{CE} (~ 0.3V) - faster switching and no tendency for thermal runaway.
However input capacitance can cause problems for high speed switching and it has a higher input turn-on voltage,(~3V as op-posed to ~0.7V);

Over to you:

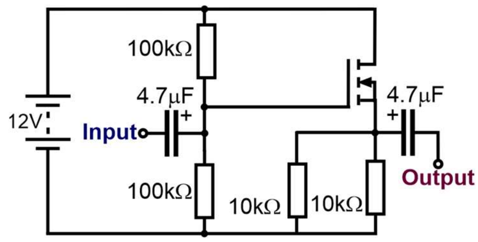
Common-source amplifier:

- Build the circuit shown opposite, using your own layout design.
- Set the DC power supply to 12V.
- Connect the input to a signal generator, set to output a signal of amplitude 50mV and frequency 1kHz.
- Connect a dual-channel oscilloscope to display the input and output signals.
- Obtain a trace showing the input and output signals and save it for your rec-ords.
- Use it to estimate the voltage gain of the amplifier.



Source follower:

- Build the circuit shown opposite, again using your own layout design
- The diagram includes two DC-blocking capacitors.
- Set the DC power supply to 12V.
- Connect the input to a signal generator, set to output a signal of amplitude 2V and frequency 1kHz.
- Connect a dual-channel oscilloscope to display the input and output signals.
- Obtain a trace showing the input and output signals and save it for your rec-ords.



So what?

Common-source amplifier:

- The 10kΩ load resistor and the MOSFET share the 12V supply.
- The 10kΩ feedback resistor and the 100kΩ resistor bias the MOSFET in the saturation region.
- The ideal is to allow the output voltage to swing up and down, in response to the input signal, by as large an amount as possible.
- In other words, we aim to sit the drain terminal at ~ ½ supply voltage, i.e. ~6V.

Source follower:

- The output voltage follows the input voltage, but is about 2V lower.
- The current gain is enormous, because the input current is tiny. 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, though not as low as the emitter follower. A low output impedance means that the output will not drop under load.
- It has the advantage that the input impedance is huge, almost infinite.
- The MOSFET is in saturation, so the current across it is determined by the gate-source voltage.

A challenge:

One issue for the design of MOSFET circuits is that performance parameters vary greatly from device to device. The component values given in the circuit diagrams are not necessarily optimal for the MOSFET you are using.

- Experiment with other resistor values in both circuits to try to improve the performance.

For your records:

For each circuit:

- Copy the circuit diagrams .
- Describe the steps taken to obtain the Picoscope trace and any other results.
- Write a brief explanation of the function of each resistor and capacitor in the circuit.
- Write detailed notes of any changes you made to improve the system performance and describe the resulting effect.

Answers

Answers

Answers for Worksheet 1
Testing BJT transistors

CP4403-AN1

NPN

Switch	Base current I_B	Collector
Open	0	0
Closed	~0.5mA	50mA

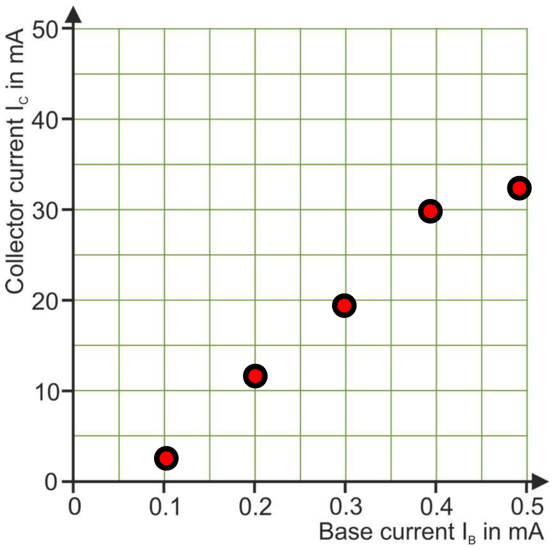
PNP

Switch	Base current I_B	Collector
Open	0	
Closed	~0.5mA	60mA

Answers for Worksheet 2
BJT transfer characteristics

CP4403-AN2

I_B in	I_C in
0	0
0.1	3
0.2	12
0.3	20
0.4	30
0.5	35

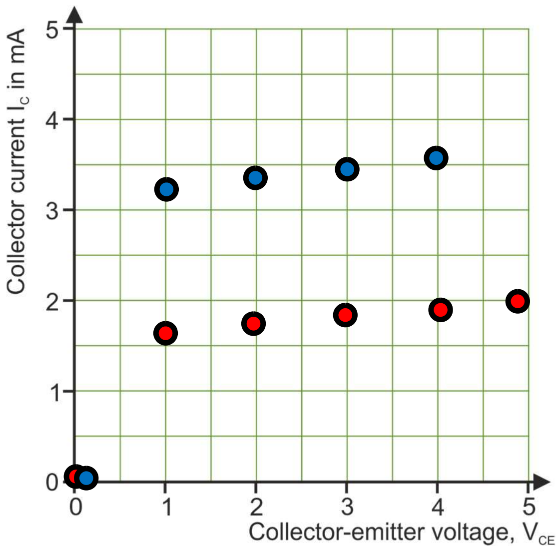


Gradient is around 100

Answers for Worksheet 3
BJT output characteristics

CP4403-AN2

V_{CE}	I_C in mA	
	R=200k Ω	R=100k Ω
0.0 V	0	0
1.0 V	1.63	3.28
2.0 V	1.71	3.37
3.0 V	1.79	3.46
4.0 V	1.88	3.55
5.0 V	1.94	



For linear portion and a 200K resistor gradient is 12. This is the internal C E resistance.

Answers

Answers for Worksheet 4
Transistor as a switch

CP4403-AN4

Switch	V_{CE}	V_L
Off	6	0
On	3 .6	2.4

Use 1k base resistor

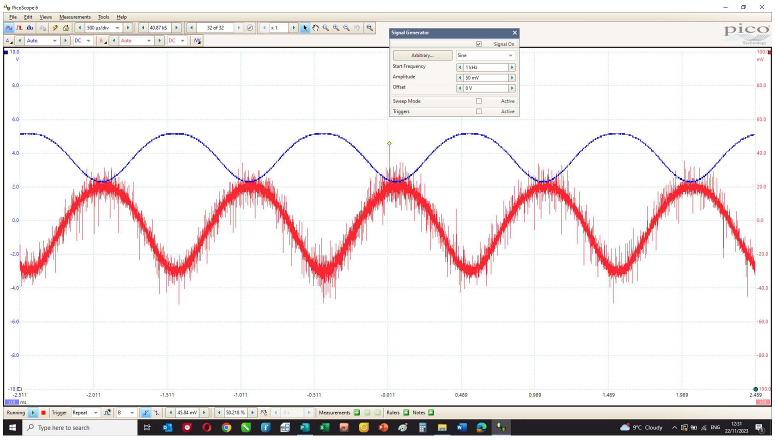
Answers for Worksheet 5
Transistor as an amplifier

CP4403-AN5

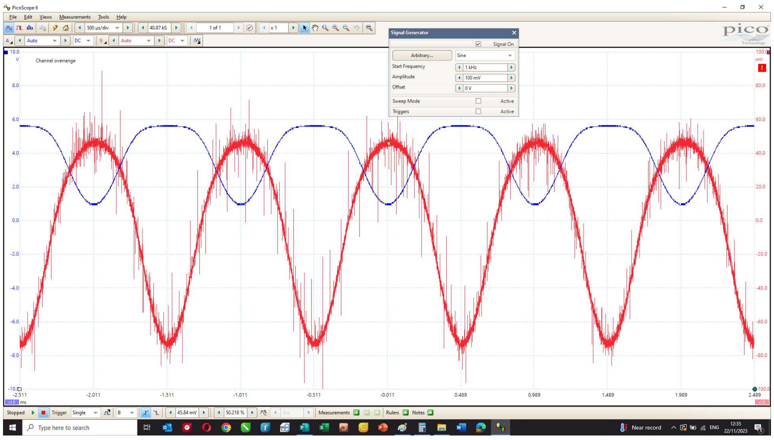
Measurement	Voltage
DC voltage at collector	3.9
DC voltage at base	0.61
DC voltage at emitter	0
AC input amplitude	50mV
AC output amplitude	3V

Peak to peak input (red) = 50mV
Peak to peak output (blue) = 3V
Gain = 60

Distortion occurs as output reaches battery voltage.



Peak to peak input (red) = 100mV
Peak to peak output (blue) = 4.5V



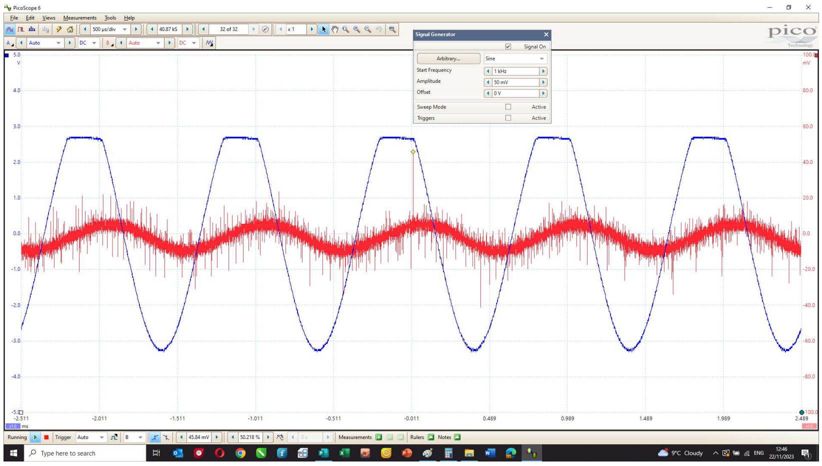
Answers

Answers for Worksheet 6
Transformer-coupled amplifier

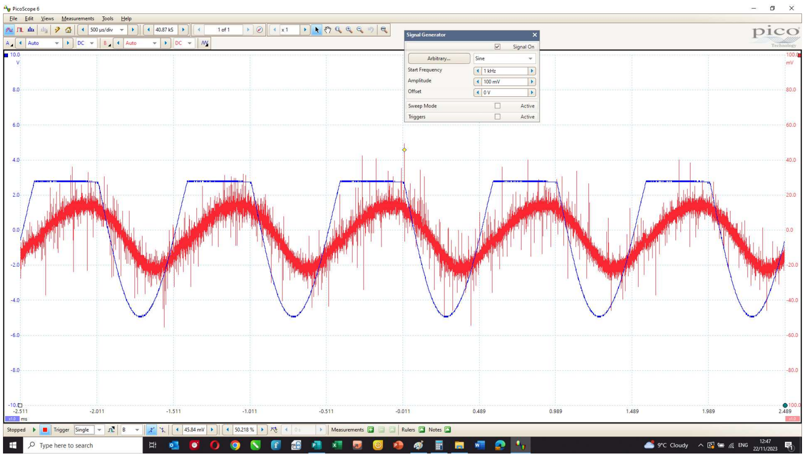
CP4403-AN6

Measurement	Voltage
AC input amplitude	50mV
AC output amplitude	6V
Voltage gain = 120	

Peak to peak input (red) = 50mV
Peak to peak output (blue) = 6V
Gain = 120



Peak to peak input (red) = 100mV
Peak to peak output (blue) = 8V



Answers for Worksheet 7
Stabilised common-emitter amplifier

CP4403-AN7

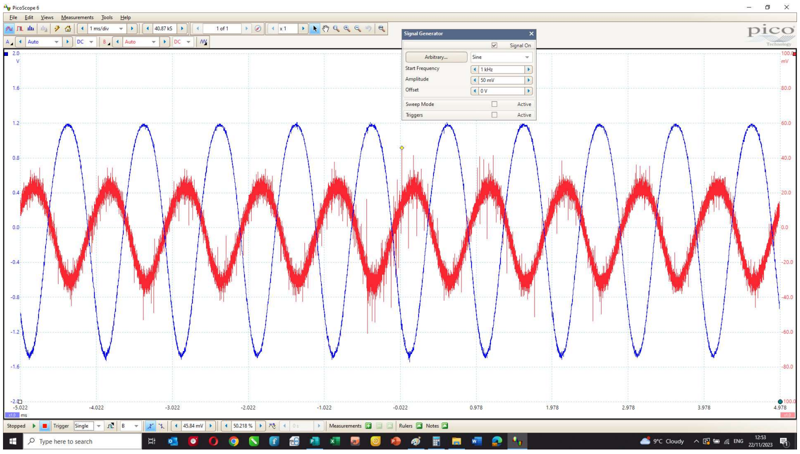
Measurement	Voltage
DC voltage at collector	
DC voltage at base	
DC voltage at emitter	
AC input amplitude	
AC output amplitude	

Answers

Answers for Worksheet 7 continued
Stabilised common-emitter amplifier

CP4403-AN7

Peak to peak input (red) = 50mV
Peak to peak output (blue) = 2.5V
Gain = 50



Answers for Worksheet 8
Stabilised common-emitter amplifier

CP4403-AN8

Input voltage V_{IN}	Output voltage V_{OUT}
0	0
1.0	0.42
2.0	1.47
3.0	2.4
4.0	3.45
5.0	4.5

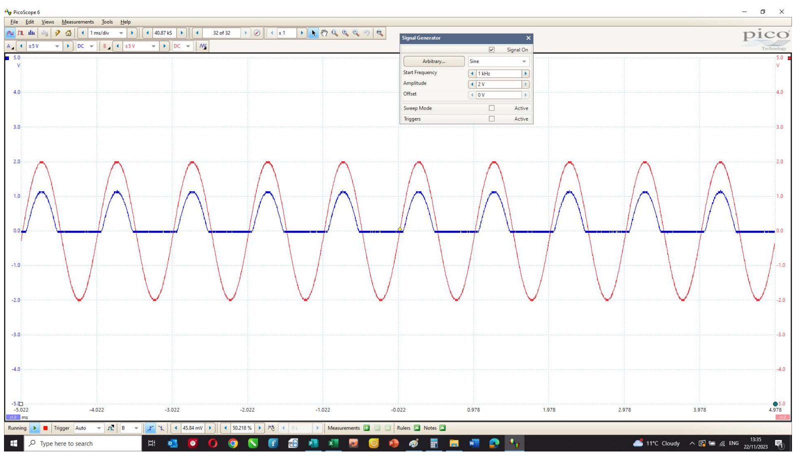
Input voltage V_{IN}	Output voltage V_{OUT}
-1.0	0V
-2.0	0V
-3.0	0V

Answers for Worksheet 9
Emitter follower - AC behaviour

CP4403-AN9

Peak to peak input (red) = 2V
Peak to peak output (blue) = 1V

Use 2 x 10K resistors for bias



Answers

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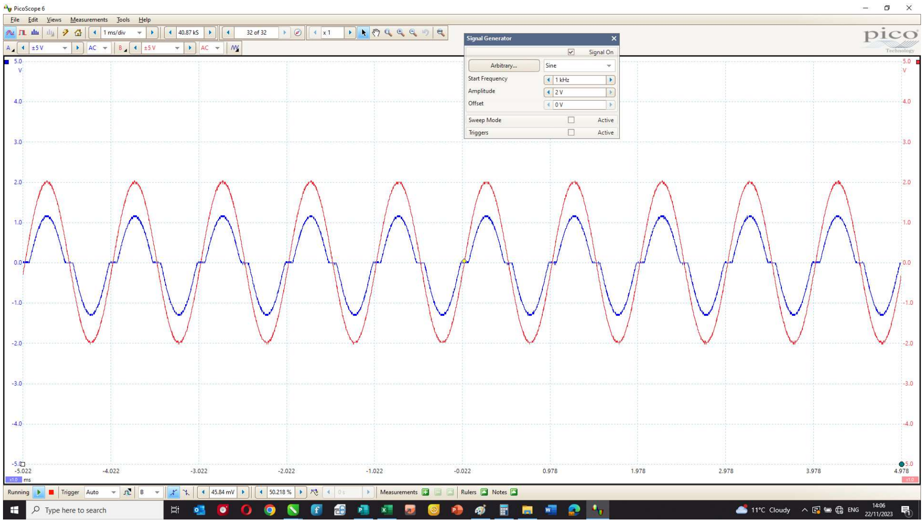
Transistor amplifiers

Answers for Worksheet 10
Push-pull follower

CP4403-AN10

Peak to peak input (red) = 2V
Peak to peak output (blue) = 2.5V



Hint: to get the low distortion push pull follower to fit on a single Locktronics base board turn the board through 90 degrees.

Answers for Worksheet 11
FET transfer characteristics

CP4403-AN11

JFET transfer characteristics

Input V_{GS}	Output I_D
0	11.25
-0.4	9.9
-0.6	7.7
-0.8	5
-1.0	3
-1.2	1.46
-1.4	0.3

MOSFET transfer characteristics

Input V_{GS}	Output I_D
0	0
1.6	0
1.8	0.26
2	3.2
2.2	9
2.4	12
2.6	12

A MOSFET with transconductance of 30mS and voltage of 3V will have a drain current of about 100mA

Answers

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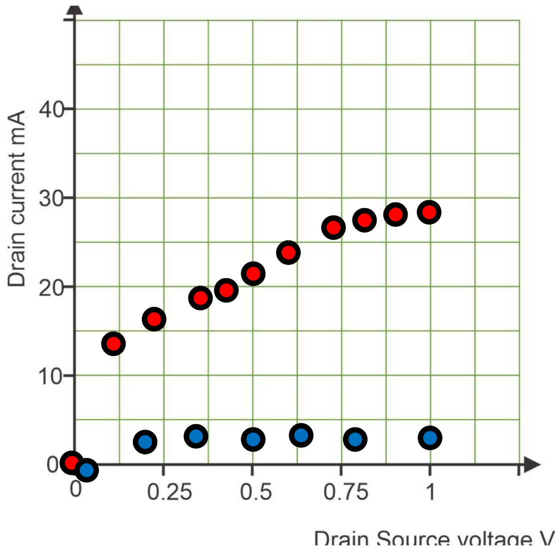
Transistor amplifiers

Answers for Worksheet 12
FET output characteristics

CP4403-AN12

V_{DS}	V_{GS} = 2.2V	V_{GS} = 2.4V
	I_D in mA	I_D in mA
0.0 V	0	0
0.1 V	1.38	14
0.2 V	1.6	16.9
0.3 V	1.8	19
0.4 V	1.96	19
0.5 V	2.08	22
0.6V	2.23	24
0.7V	2.36	25
0.8V	2.48	27
0.9V	2.6	28
1.0V	2.73	29



Answers for Worksheet 13
MOSFET switch

CP4403-AN13

Switch	V_{DS}	V_L
Off	6	0
On	0	6

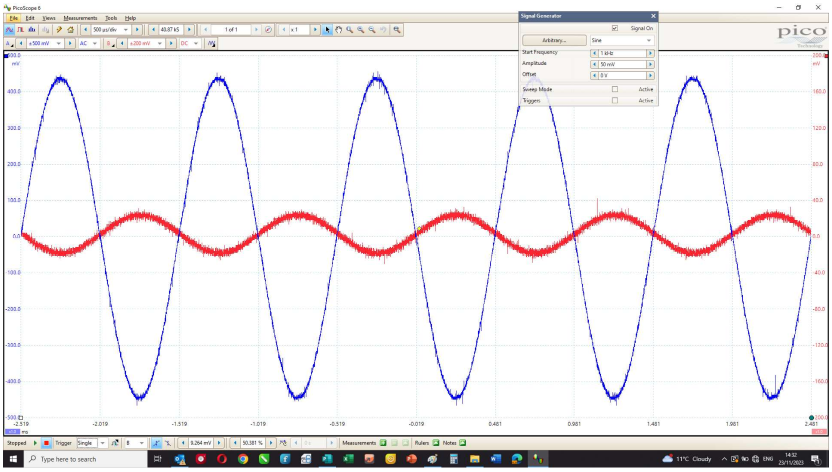
Switch A	**Switch B**	**MOSFET**
Open (off)	Open (off)	6V
Open (off)	Closed (on)	0
Closed (on)	Open (off)	0
Closed (on)	Closed (on)	0

Answers

Transistor amplifiers

Answers for Worksheet 14
MOSFET applications

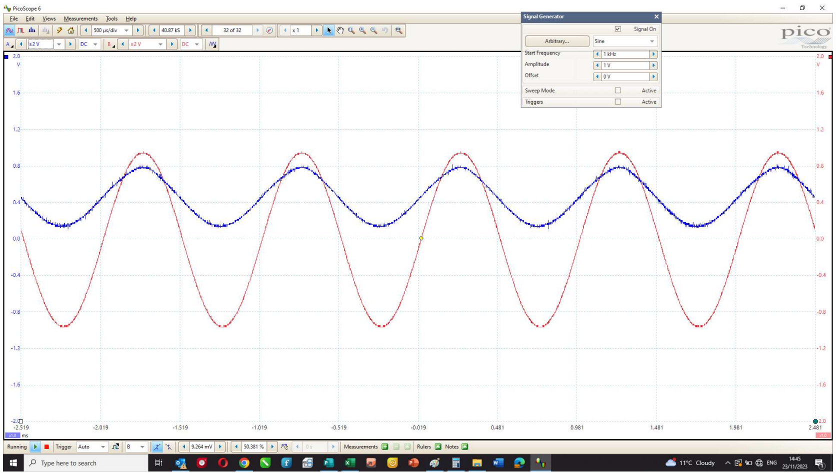
CP4403-AN14



Common-source amplifier:

Peak to peak input (red) = 50mV
Peak to peak output (blue) = 0.9V
Gain = 18

Source follower:



Peak to peak input (red) = 1V
Peak to peak output (blue) = +/- 900mV
Gain = 0.35

Student handout

Student handout

Transistor amplifiers

Worksheet 1

Testing BJT transistors

CP4403-ST1

NPN

Switch	Base current I_B	Collector
Open	0	
Closed	~0.5mA	

PNP

Switch	Base current I_B	Collector
Open	0	
Closed	~0.5mA	

- Copy the circuit diagrams for the npn and pnp transistor tests.

NPN

PNP

- Write instructions so that one of your colleagues could carry out the tests.

- Explain to your colleague why the base current is likely to be around 50µA when the switch is pressed.

- Estimate the base current if the 10kΩ resistor were swapped for a 100kΩ resistor.

- Copy the formula for current gain h_{FE}:

Student handout

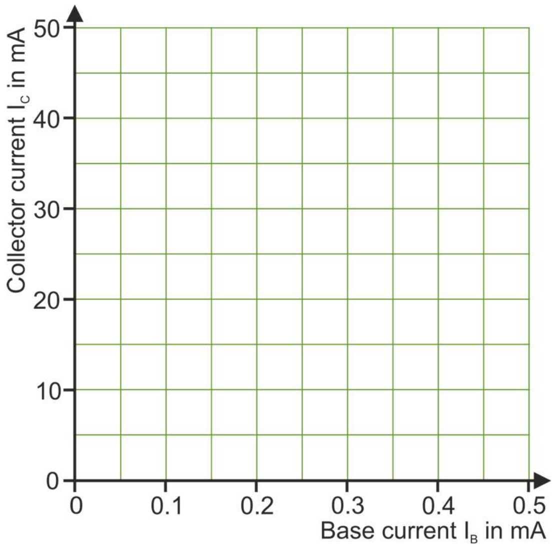
Worksheet 2

BJT transfer characteristics

CP4403-ST2

Current transfer characteristic

I_B in	I_C in
0	
0.1	
0.2	
0.3	
0.4	
0.5	



A challenge:

Test different BC108 transistors (or any other type available to you) with a multimeter transistor tester to see the variation in current gain.

For your records:

- Copy the circuit diagram for the circuit you set up in this investigation.

- Describe the steps taken to obtain the current transfer characteristic for the transistor.

- Measure the gradient of the graph you plotted to give you an estimate of the current gain of the transistor.

Student handout

- Identify the transistor used on the transistor carrier. Look for the writing on the transistor body. It may be a ZTX 451. Use the internet to check the manufacturer's value for current gain with the one you obtained.

- Copy the following table and complete it.

Transistor type	**Current gain**	**Base current**	**Collector current in mA**
BC108	500	10mA	
BFY51	60		300
BD437		8mA	500
BC546	200		100
2N3904		100mA	12

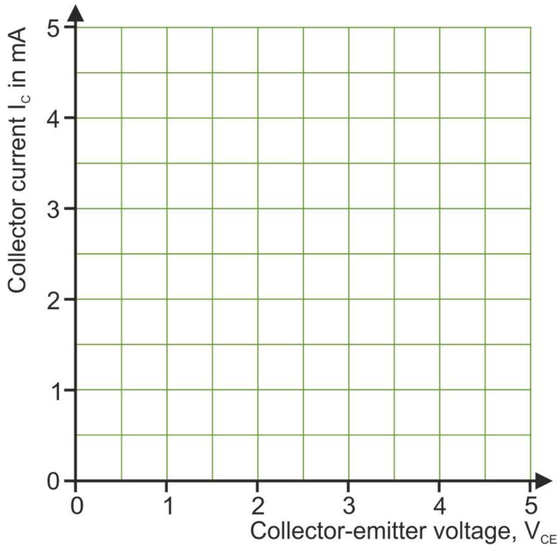
Student handout

Transistor amplifiers

Worksheet 3
BJT output characteristics

CP4403-ST3

V_{CE}	I_C in mA	
	R=200k Ω	**R=100k Ω**
0.0 V		
1.0 V		
2.0 V		
3.0 V		
4.0 V		
5.0 V		



For your records:

- Copy the circuit diagram for the circuit you set up in this investigation.
- Describe the steps taken to obtain the output characteristic for the transistor.

- Measure the gradient of the linear portion of the two graphs you plotted and hence obtain the output resistance.

Student handout

Worksheet 4
Transistor as a switch

CP4403-ST4

Switch	V_{CE}	V_L
Off		
On		

For your records:

- Copy the circuit diagram for the transistor switch given at the start of the investigation.

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

- Assuming that the base-emitter voltage is 0.7V when the transistor is on, estimate the base current when the switch is closed in:
    - the lamp circuit;
    - the motor circuit.

- Explain why the base resistor in the motor circuit has a much lower value than that used in the lamp circuit.

- 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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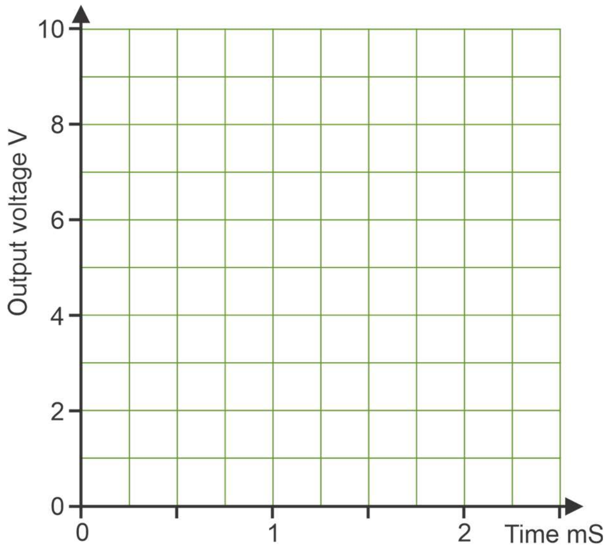
locktronics
Transistor amplifiers

Worksheet 5
Transistor as an amplifier
CP4403-ST5

Measurement	Voltage
DC voltage at collector	
DC voltage at base	
DC voltage at emitter	
AC input amplitude	
AC output amplitude	



For your records:

- Copy the circuit diagram for the transistor amplifier.

- Explain what your oscilloscope traces show.

- Use them to estimate the voltage gain before distortion sets in.

- Explain why the output becomes distorted for larger input signal amplitudes.

Student handout

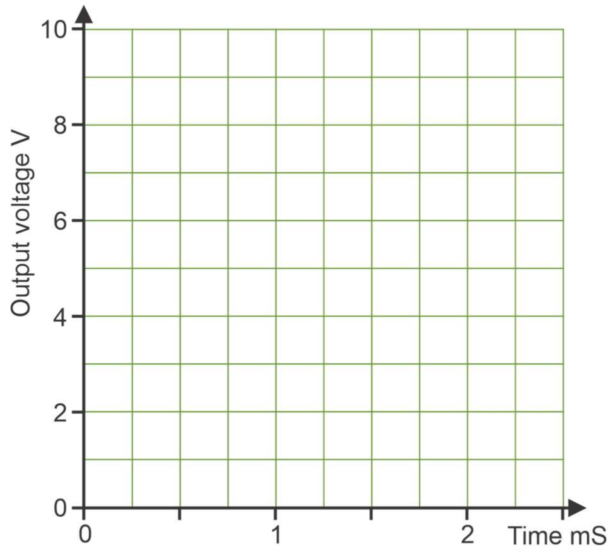
Transistor amplifiers

Worksheet 6

Transformer-coupled amplifier

CP4403-ST6

Measurement	Voltage
AC input amplitude	
AC output amplitude	
Voltage gain =	



For your records:

- Copy the circuit diagram for the transistor amplifier.

- Explain what your oscilloscope traces show.

- Use them to estimate the voltage gain:

Student handout

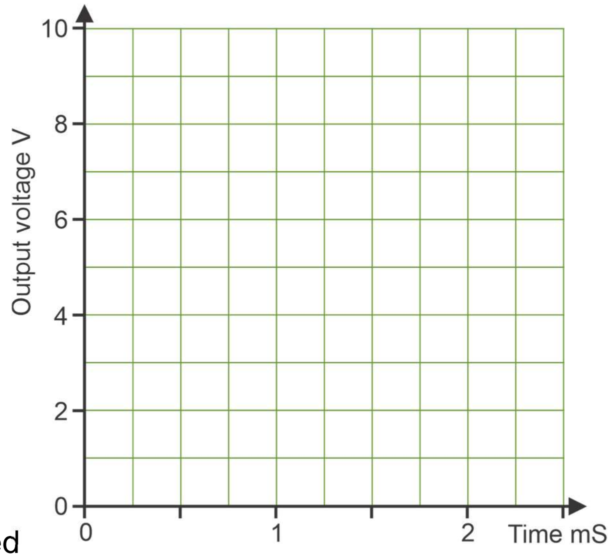
Transistor amplifiers

Worksheet 7

Stabilised common-emitter amplifier

CP4403-ST7

Measurement	Voltage
DC voltage at collector	
DC voltage at base	
DC voltage at emitter	
AC input amplitude	
AC output amplitude	



For your records:

- Copy the circuit diagram for the transistor amplifier.

- Describe the function of the voltage divider connected to the base of the transistor.

- How does the emitter resistor provide negative feedback?

- Explain how the emitter resistor bypass capacitor affects voltage gain.

- Using resources such as the internet or text-books, explain what is meant by ‘negative feed-back’ and describe its effects in applications like the current one.

Worksheet 8
Emitter follower behaviour

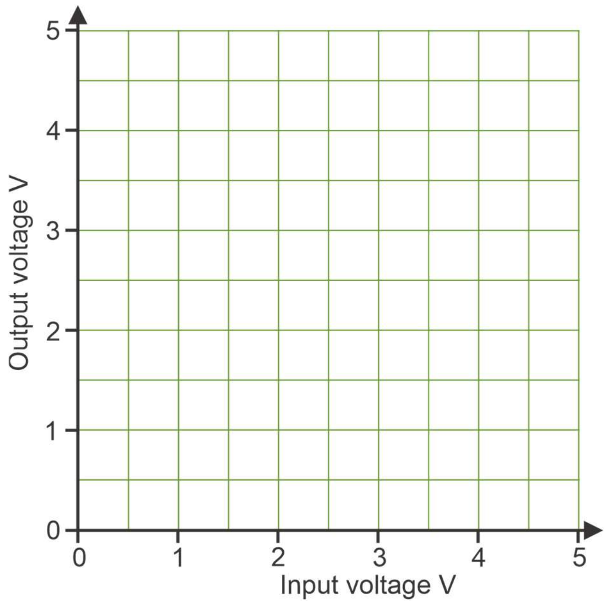
CP4403-ST8

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

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

For your records:

- Copy the circuit diagram for the transistor amplifier.



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

- Copy the expressions given above for the emitter follower relationship, its voltage gain, and its current gain.

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

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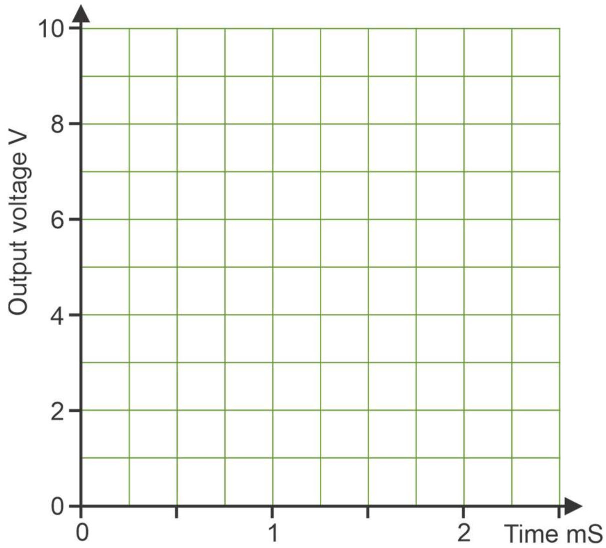
Transistor amplifiers

Worksheet 9
Emitter follower - AC behaviour

CP4403-ST9



For your records:

- Copy the initial circuit diagram for the emitter follower

- Explain the purpose of the two capacitors.

___

___

___

- Explain why the circuit creates distortion.

___

___

___

- Draw the circuit diagram for the modification given in the second challenge.

- Explain why this modification should reduce the distortion.

___

___

___

Student handout

Worksheet 10
Push-pull follower

CP4403-ST10

For your records:

- Copy the initial circuit diagram for the push-pull follower.

- Explain why the circuit creates cross-over distortion.

- Draw the circuit diagram for the modification given in the second challenge - including DC blocking capacitors.

- Explain why this modification should reduce distortion.

Student handout

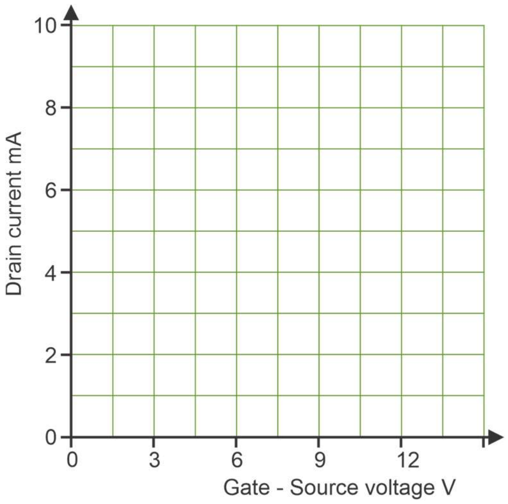
Worksheet 11
FET transfer characteristics

CP4403-ST11

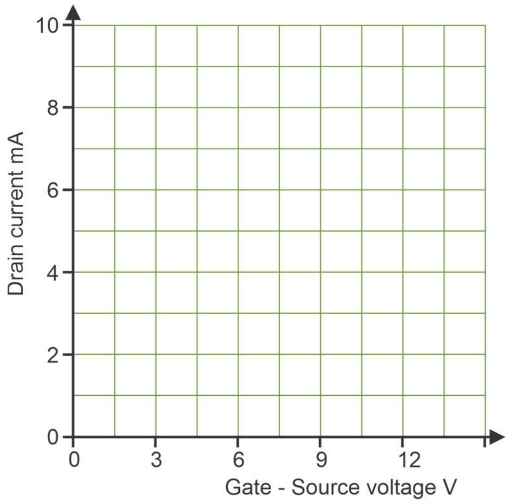
Input V_{GS}	Output I_D
0	
-0.1	
-0.2	
-0.3	
-0.4	
-0.5	

Input V_{GS}	Output I_D
-0.6	
-0.7	
-0.8	
-0.9	
-1.0	

JFET



MOSFET



For your records:

- Explain what is meant by the term 'transfer characteristic' for a FET.

- Write an explanation of less than 100 words, for a fellow student, on the differences in the way a depletion-mode JFET and an enhancement-mode MOSFET are used in a circuit.

- Draw the circuit diagram for the investigation into the MOSFET transfer characteristic and write a simple list of instructions for a fellow student, including how to process the results.

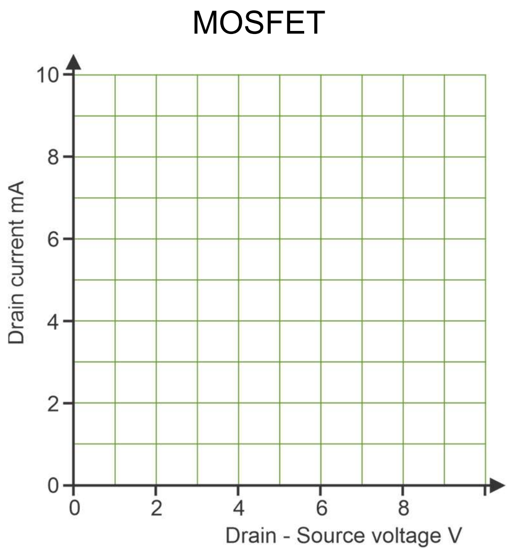
- When a MOSFET has a transconductance of 30mS, the drain current will be ………. for a gate-source voltage of 3.0V.

Student handout

Worksheet 12
FET output characteristics

CP4403-ST12

V_{DS}	V_{GS} = 2.2V	V_{GS} = 2.4V
	I_D in mA	I_D in mA
0.0 V		
0.1 V		
0.2 V		
0.3 V		
0.4 V		
0.5 V		
0.6V		
0.7V		
0.8V		
0.9V		
1.0V		



For your records:

- Copy the circuit diagram for the circuit you set up in this investigation.

- Describe the steps taken to obtain the MOSFET output characteristic.

- Measure the gradient of the two graphs you plotted to obtain estimates of $R_{DS(on)}$.

- Complete the following:
- A 2N7000 MOSFET has a value of $r_{DS(on)}$ of 5Ω. A drain current I_D of 200mA will dissipate ……….mW in the device.

Student handout

Worksheet 13
MOSFET switch

CP4403-ST13

Switch A	Switch B	MOSFET
Open (off)	Open (off)	
Open (off)	Closed (on)	
Closed (on)	Open (off)	
Closed (on)	Closed (on)	

Input A	Input B	Output
0	0	
0	1	
1	0	
1	1	

For your records:

- Copy the circuit diagram for the MOSFET switch and for the OR gate:

- Write a brief explanation (no more than three sentences,) for a fellow student on why the circuit can be described as a switch.

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____

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- Use the datasheet for the `RFP30N06LE` to find the following information for this MOSFET:
  - 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.

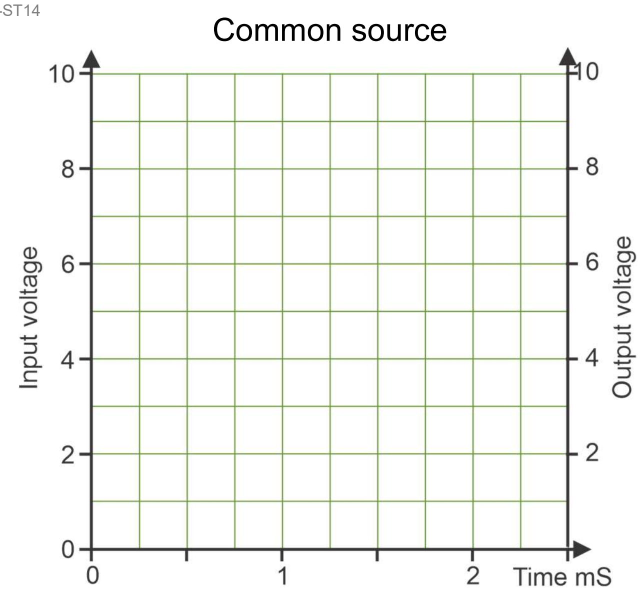
____

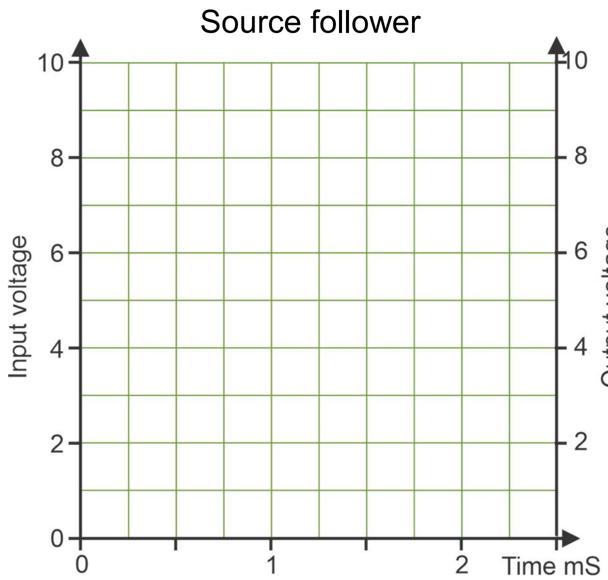
Student handout

locktronics
Transistor amplifiers

Worksheet 14
MOSFET applications

CP4403-ST14





For your records:

- Copy the circuit diagrams.

- Describe the steps taken to obtain the Picoscope trace and any other results.

- Write a brief explanation of the function of each resistor and capacitor in the circuit.

- Write detailed notes of any changes you made to improve the system performance and describe the resulting effect.

Instructor guide

About this course

Introduction

The course is essentially a practical one. Locktronics makes it simple to construct and test electrical circuits. The result mirrors the circuit diagram, thanks to the circuit symbols printed on the carriers.

Aim

The course explores the use of bipolar and field effect transistors in switching and in amplifier circuits.

Learning Objectives

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

- set up circuits to test npn and pnp transistors and analyse the results;
- state and use formulae linking current gain and the emitter current to collector and base currents;
- set up a circuit to obtain the current transfer characteristic of a bipolar transistor;
- use the current transfer characteristic curve to estimate the current gain of the transistor;
- set up a circuit to obtain the output characteristic of a bipolar transistor;
- use the output characteristic curve to estimate the output resistance of the transistor;
- state the electrical properties of a switch;
- draw the circuit diagram for a npn transistor used to switch on a lamp or a motor;
- explain why an inverse parallel diode is needed to protect the transistor when switching inductive loads;
- relate the size of the base resistor to base current in a transistor switch;
- state the accepted value (~ 0.7V,) for the base-emitter voltage in a conducting bipolar transistor;
- draw the circuit diagram for a common-emitter single-stage amplifier using a base bias resistor;
- define the term 'voltage gain' for an amplifier and use an oscilloscope to measure it;
- explain the use of DC blocking capacitors to couple input and output subsystems;
- describe the effect of changes in input voltage on base current, collector current and output voltage in a
  common-emitter single-stage amplifier;
- explain what is meant by the term 'distortion' applied to the performance of amplifiers;
- explain why the output is distorted for large input signal amplitudes;
- describe the basic components of a transformer;
- distinguish between 'step-up' and 'step-down' transformers;
- draw the circuit diagram for a common-emitter single-stage amplifier using transformer coupling;
- state the maximum power transfer theorem;
- draw the circuit diagram for a common-emitter stabilised amplifier using a voltage divider to deliver base bias, an emitter resistor and an emitter resistor decoupling capacitor;
- explain the function of the emitter resistor and its bypass capacitor in this circuit;
- use a log-log grid to plot the frequency response of an amplifier;
- draw the circuit diagram for an emitter follower circuit and explain its use in audio systems;

Bill Of Materials

What the student will need:

To complete this course, the student will need the parts shown in the table.
In addition the student will need:

- LK9071-2 Basics of electricity kit
- 1 function generator capable of generating sinusoidal AC signals with frequencies up to 10kHz.
- 1 oscilloscope with two traces.
- Two digital multimeters
- LK9345 transistor add-on pack

Power source:
The investigations in this module require two HP2666 DC power sources.

The HP2666 is an adjustable DC power supply offering output voltages of either 3V, 4.5V, 6V, 7.5V, 9V or 12V, with currents typically up to 1A. The voltage is changed by turning the selector dial just above the earth pin until the arrow points to the required voltage. (The instructor may decide to make any adjustment necessary to the power supply voltage, or may allow students to make those changes.)

Transistor add-on kit contents		
Qty	Code	Description
1	HP2045	Shallow tray
1	HP2666	Power supply
1	HP4039	Tray Lid
1	HP7750	Daughter tray foam cutout
1	HP8600	Crash Foam 360mm x 260mm, thickness 25mm
1	LK2340	AC voltage source carrier
1	LK2347	6V MES bulb
1	LK3982	Voltmeter 0V to 15V
1	LK4123	2:1 transformer
1	LK5146	JFET transistor carrier
1	LK5203	10k ohm resistor carriers
1	LK5205	270 ohm resistor carriers
1	LK5208	250 ohm potentiometer carriers
2	LK5218	100k ohm resistor carriers
1	LK5224	47uF capacitor carrier
1	LK5240	Transistor, NPN, RHF
1	LK5243	Power diodes
5	LK5250	connecting links
1	LK5256	Transistor, PNP, LHF
2	LK6206	4u7F capacitor carriers
1	LK6207	push-to-make switch carriers
1	LK6219	560ohm resistor carriers
1	LK6238	200k ohm resistor carriers
1	LK8011	Power MOSFET carrier
1	LK8275	Power supply carrier with battery symbol
1	LK8932	Speaker
1	LK9381	Milliammeter

The contents of LK9345 Transistor add-on pack

Prior Knowledge

It is recommended that students have followed the 'Electricity Matters 1'and 'Electricity Matters 2' or have equivalent knowledge of concepts such as current, voltage, and resistance, and can construct and test circuits, using a range of measuring instruments, including multimeters 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 should be printed / photocopied / laminated, preferably in colour, for the students' use. They should make their own notes, and carry out the tasks identified in the 'For your records' sections. 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.
- a section headed 'For your records', to be copied and completed in students' exercise books.

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 7 and 10 hours to complete the worksheets. It is expected that a similar length of time will be needed to support the learning that takes place as a result.

Instructor Guide

locktronics

Transistor amplifiers

Worksheet	Notes for the Instructor	Timing
Introducing transistors **Introducing the digital oscillo-scope**	This course begins with an overview of the range and types of transistor. Much of this information may be familiar to the student. Most will be developed during the course. The instructor, knowing the students' background can judge how much 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. Power supply possibilities - the layout diagrams are arranged so that the new Locktronics power supply can be clipped onto the baseboard and used directly. Other power supplies can be connected using the Locktronics power supply carrier or 4mm leads. The course assumes that students have access to dual-trace oscilloscopes. If these are computer-based, like the 'Picoscope' range, even better as they can then save their traces for future reference. The instructor could project some during tutorial work to make appropriate points.	**15 - 30 mins**
1 CP4403-TN1	In the first worksheet, students carry out some simple functional checks on a transistor. A brief introduction to this activity could be useful and students should be reminded that a transistor comprises two p-n junctions and that each acts like a diode, conducting current in one direction only. Instructors may wish to demonstrate the use of a multimeter with a transistor check facility or a dedicated transistor tester. Alternatively, where these are not available, instructors could show how forward and reverse resistance readings can be used to indicate the 'go/no-go' status of each of the junctions within a transistor. The method that students adopt in this worksheet involves measuring the collector current of a transistor with and without base current applied. With zero base current there should be no measurable amount of collector current, (leakage current should be negligible). With base current applied there should be an observable collector current. The aim is not to measure current gain itself. The needle milliammeter has only to show that the collector current is much bigger than the base current. With the values used, the base current should be approximately 0.5mA. With a typical value of common-emitter current gain (e.g. 100) this should result in a collector current of around 50mA. The 100 ohm resistor acts as a load to limit the current through the transistor. Instructors might find it useful to provide students with some defective transistors (i.e. open-circuit and/or short-circuit devices). Students should then be able to identify 'good' and 'bad' devices by applying the procedure that they have used in this worksheet investigation.	**30 - 40 mins**

Worksheet	Notes for the Instructor	Timing
2 CP4403-TN2	This practical exercise involves making series of measurements to allow students to plot the transfer characteristic (collector current vs base current) for a transistor connected in common-emitter mode. Students should copy the table into their work books and use it to record their measurements. They will need graph paper to use for plotting the transfer characteristic to add to their records. Suitable scales are suggested in the worksheet. Students should have access to sample characteristics for a variety of common NPN transistors (e.g. BC108 or BC548) so that they can compare these with their own graphs. They should be invited to comment on the shape of the graph. They should find that it is almost perfectly linear, leading to the concept of current gain, the slope of the graph. They may need support in calculating the gradient, depending on their previous experience and mathematical ability. One approach is to give examples in which students replace the values used with their own measured values. It might also be useful to compare the results obtained by different students. The analysis in the 'So what' section introduces the idea of saturation. The instructor may need to elaborate on this with some students. The final section gives practice in the use of the current gain formula. The instructor may wish to extend this exercise if students find progress difficult.	**25 - 35 mins**
3 CP4403-TN3	Here, an approach similar to the previous one is used to obtain the output characteristic (collector current vs collector-emitter voltage) for the transistor. Once again, they keep a record of their results, both as a table and as a graph. The shape is less obvious and the instructor may need to prepare them and discuss the significance of the graph. As a simplification, the graph could be drawn as two straight lines, one before the 'knee' and one after. It may not be obvious to some what 'output resistance' means, in which case the instructor may wish to explore the idea of the equivalent circuit for the output of the transistor, as a voltage source and a series resistance or current source and a parallel resistance. In either case, the aim is to simplify calculating what the transistor output circuit will do in different circumstances.	**25 - 35 mins**
4 CP4403-TN4	In this worksheet students investigate the use of a transistor as a switch. They should begin by constructing and testing the lamp switching circuit, making voltage measurements to verify that the transistor is operating under saturated conditions when the switch is closed. The circuit is operated by a push-switch but could equally be a light-operated, temperature-operated, etc. system. The effect of the transistor is shown by trying to operate the system without it, 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. It is assumed that students know the electrical properties of a switch. The instructor might wish to revisit these using circuit shown at the bottom of the first page of the worksheet. This could be done as a demonstration. In the second 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.	**30 - 40 mins**

Worksheet	Notes for the Instructor	Timing
5 CP4403-TN5	Students explore a practical application of transistors - a simple common-emitter amplifier stage. In order to cope with the wide variation in common-emitter current gain, the base bias current is derived from the collector of the transistor rather than from the positive supply rail, giving control through negative feedback. This is not mentioned in the text, but the instructor could take the opportunity to introduce the topic here. Instructors will need to explain the need for, and meaning of, bias and the function of the collector load resistor. Worked examples, involving calculation of the voltage and current at the base and collector of the transistor, could be extremely useful and should yield typical values against which students can compare their measured results. The circuit uses DC blocking capacitors to isolate the transistor amplifier from the effect of any DC components in the input signal and isolate the output circuit from DC components in the transistor amplifier. In reality, these are optional in this circuit, as the signal generator is unlikely to output a DC level as well as the AC signal. In general terms, the capacitor values are chosen to have a low reactance relative to the input and output circuits at the lowest signal frequency used in the amplifier. It should be remembered that, in general use, they act as high-pass filters and so skew the frequency response of the amplifier. Students need a dual-channel oscilloscope (or equivalent virtual instrument) with which to display the input and output waveforms. Where necessary, some instruction or demonstration on using this should be given before the students begin their own measurements. It is important to remind students that the common ground connection to the oscilloscope should be taken to the 0V supply rail. Typical voltage measurements for this investigation are: Collector voltage = 3.8V Base voltage = 0.67V Students should set the oscilloscope controls to display at least two cycles of the input and output waveforms on a common time scale. They then sketch the waveforms that they have observed, making sure to include labelled axes of voltage and time, or capture the data as an image file. They measure the peak-to-peak voltage at the input and output in order to calculate the voltage gain of the amplifier. Typically they obtain an output of around 4V peak-peak for a 50mV peak-peak input at 1kHz - a voltage gain of around 80. Finally, students investigate the effect of over-driving the input of the amplifier by increasing the input voltage from around 50mV pk-pk to around 100mV pk-pk. They should find that the maximum undistorted output voltage is around 5V pk-pk. Using a speaker as the load, they can hear the increased volume and distortion compared with the signal inputted from the signal generator. The effect of changing the input voltage on base current, collector current and output voltage is described in the ‘So what’ section.	**40 - 55 mins**

Worksheet	Notes for the Instructor	Timing
6 CP4403-TN6	Similar to Worksheet 5, here the amplifier is transformer-coupled rather than capacitor-coupled. Once again, students need to understand bias voltage. They may or may not be familiar with transformers from other parts of their studies. The instructor will judge how much support they need to understand this device. Its structure and behaviour is described in the 'So what' section, but additional worked examples, involving calculations using the transformer's turns ratio (i.e. 2:1) could be extremely useful. The instructor could explore reasons for the improved efficiency, building on the issue of reduced heat loss in the load resistor, mentioned in the analysis. Once again, students will need a dual-channel oscilloscope (or equivalent) to display the input and output signals. Depending on their ability, this may need further support from the instructor. Typical voltage measurements for this investigation are: Collector voltage = 6.2V Base voltage = 0.69V Again, they display around two cycles of the input and output on a common time scale and sketch the waveforms or capture the data as an image file. Students measure input and output voltages in order to calculate the voltage gain of the amplifier. Typical values, 5V pk-pk output for a 20mV pk-pk input infer a voltage gain of around 250 at 1kHz . (This increase in gain results from the greatly increased value of AC collector load resistance). Once again, students should investigate the effect of over-driving the input of the amplifier by increasing the input voltage.	**30 - 40 mins**
7 CP4403-TN7	This worksheet is similar to Worksheets 5 and 6 but now students construct and test a fully-stabilised common-emitter amplifier stage. They will again need a dual-channel oscilloscope (or equivalent virtual instrument) with which to display the input and output waveforms and again, for some, this can involve extra help or close supervision by the instructor. Typical voltage measurements are as follows: Collector voltage = 3.55V Base voltage = 1.43V Emitter voltage = 0.76V As in previous exercises, students should make the adjustments necessary to display around two cycles of the input and output waveforms on a common time scale and either sketch the signals or capture them as an image file. They measure the peak-to-peak voltages at the input and output in order to calculate the voltage gain of the amplifier. Typical results are an output of 3V pk-pk for a 50mV pk-pk input at 1kHz, inferring a voltage gain of around 60. Students should compare this value with those obtained in Worksheet 4 and Worksheet 5. Instructors should check that students understand the functions of the base voltage divider, the emitter resistor (in providing negative feedback,) and the bypass capacitor in the circuit, following the descriptions developed in the 'So what' section. Negative feedback always reduces voltage gain. The rule-of-thumb for the bypass capacitor is that its reactance at the lowest frequency of interest should be ~0.1 x the emitter resistance. A worked example will be extremely useful and this should involve calculation of the bias voltages and currents, showing the effect of both an increase and decrease in collector current.	**35 - 45 mins**

Worksheet	Notes for the Instructor	Timing
8 CP4403-TN8	This worksheet moves from small-signal amplifier to large-signal amplifier, from voltage amplifier to power amplifier, from common-emitter configuration to common-collector configuration. The instructor can expand on these terms to ensure that students appreciate that the function of this circuit is different. Its activities mirror those of worksheet 2, the behaviour of the common-emitter configuration. The first step is to convey the meaning of 'follower', a term used for a number of subsystems in electronics. To do this, they watch the analogue voltmeters - as the input voltage changes, the output follows. More accurate measurements then follow, using a multimeter (or two). This reveals that there is a small difference between input and output voltage due to the forward voltage drop across the base-emitter junction. It is also shown that the circuit does not respond to negative voltages. These results are analysed in the 'So what' section and are plotted as a graph in the 'For your records' section. It is shown that the subsystem has a voltage gain of ~1 and a current gain of ~h_{FE} . Typically, a power transistor has a current gain of ~ 50. Overall then, this subsystem has a power gain (= voltage gain x current gain). The students are then challenged to carry out the same investigation using a pnp transistor. This prepares the way for the push-pull follower. The instructor needs to check carefully that their modification will work. The polarities of the power supply and the meters must be reversed.	**35 - 55 mins**
9 CP4403-TN9	The next step is to look at the behaviour of the emitter follower when an AC signal is applied to it. In principle, DC blocking capacitors are used, though, as pointed out earlier, they are unlikely to be needed for an input produced by a signal generator. In fact, if they are used, the overall voltage gain will be reduced. The amplitude of the input, (3V), is much larger than in previous exercises. Support from the instructor might be needed to ensure this. As can be anticipated from the outcome of the previous investigation, the emitter follower does not respond to the negative half of the input signal. The output signal faithfully reproduces the positive half. When a speaker replaces the 1kΩ load, the sound is harsher than the original. The reason is that the frequency spectrum of the now-truncated output, contains a series of high frequency components instead of just the single signal generator frequency. One of the challenges invites students to set up permanent base bias for the emitter follower, to sit it around mid-way between the power rails when there is no signal. As a result, the transistor is conducting all the time. Ideally the negative half of the AC input subtracts from this bias, but never forces the transistor out of conduction, and the positive half never causes saturation. The guidelines for choosing values for the voltage-divider resistors are given in the challenge. The disadvantage of this arrangement is that DC currents flow all the time through the resistors in the voltage divider and in the load, dissipating energy as heat and reducing energy efficiency, battery life etc.	**25 - 40 mins**

Worksheet	Notes for the Instructor	Timing
10 CP4403-TN10	The previous worksheet showed how to overcome the distortion of the emitter follower with a voltage divider providing permanent base bias. However, that was inefficient. Here is another solution, the push-pull follower.It uses a npn transistor to handle the positive half of the input signal and a pnp transistor to handle the negative half. Both feed current to the output but these do not interfere as when the npn transistor conducts, the pnp is effectively open circuit, and vice-versa. The disadvantage of this circuit is that it uses a 'split power supply', requiring three voltage rails, here +12V, 0V and -12V. As in the previous circuit, although DC blocking capacitors are shown in the 'official' circuit diagram, they are not used in the layout as there is unlikely to be a DC component in the signal from the signal generator. Although the output signal now contains both positive and negative portions, there is still evidence of some distortion, called cross-over distortion. The transistors do not start to conduct immediately, as we have seen. It takes an input signal of at least ~0.5V to start conduction. As a result, when the input signal is between ~+0.5V and -0.5V, neither transistor conducts and the output is 0V. Connecting a speaker to the output reveals the slight harshness caused by this distortion. One of the challenges looks at removing this distortion by use of a voltage divider of two resistors and two diodes. These are connected in such a way that the base of the npn transistor is lifted by ~0.7V and so any positive voltage in the signal causes corresponding conduction in the transistor. Equally, the base of the pnp transistor is pushed down by ~0.7V so that any negative voltage in the signal has an effect.	**25 - 40 mins**
11 CP4403-TN11	This worksheet introduces field-effect transistors. Invented before BJTs, their development had to await advances in processing technology. No attempt is made to study the underlying conduction mechanisms. The instructor will judge how much of this to incorporate into the course. The worksheet compares the performances of two FETs, a JFET operating in depletion mode and a MOSFET operating in enhancement mode. An advantage of the latter can be seen in the circuit diagram - it needs only two power rails, not three. The procedure is similar to that used for the BJT in worksheet 2, except that here the independent variable is gate-source voltage, not base current. The resulting graphs are similar in shape, but displaced along the voltage axis. The worksheets begin to be more open-ended, requiring students to apply the skills learned in previous worksheets to new situations. So it is here with the investigation into the transfer characteristic of the MOSFET. The instructor may require to see the layouts before the students activate them. The most significant concept to convey here is transconductance, g_m. It is the inverse of resistance. The SI unit is called the siemens, (S), but is also known as the 'mho' (i.e. 1 siemens = 1 mho). One calculation example is given in the 'For you records' section, but the instructor may choose to add others to ensure that students understand the concept. Please notice the warning about the danger of applying positive voltages to the gate of the JFET and stress it to students!	**25 - 40 mins**

Worksheet	Notes for the Instructor	Timing
12 CP4403-TN12	This worksheet looks at the output characteristic of the MOSFET. Equivalent to worksheet 3, the results from both should be compared. The introduction mentions the term ‘impedance’ (briefly). Students may or may not be familiar with this and the instructor may wish to stress or ignore it depending on the outcomes specified for the course of study. The circuit includes two ‘pots’ - one to set the drain-source voltage, V_{DS}, the independent variable, the other to set the gate-source voltage, V_{GS}. To avoid a possible short-circuit of the power supply, the instructor should check that they are connected correctly in the circuit. Although the aim is increasingly to make students apply previous skills to designing their own layouts, it was felt necessary to include this one for them because of the potential confusion over connecting the ‘pots’. Although V_{GS} could be controlled by a voltage divider of two resistors, the drain current is so sensitive to it that finer control, using a ‘pot’, is necessary. The 270Ω resistor in series with it makes it easier to set the required voltages and makes it more difficult to set excessively high values of V_{GS}. The instructor could make available the output characteristics of other MOSFETs, for comparison. Some time should be spent on analysing the graphs resulting from the investigation to identify the linear and saturation regions, to see the effect that V_{GS} has on the drain current and to identify the effect on $R_{DS(ON)}$. The final part of the ‘For your records’ section invites students to research the conduction mechanism in MOSFETs. In some cases, the instructor may feel that this is not necessary.	**30-45 mins**
13 CP4403-TN13	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 this use as a switch. The other common application is in logic gates, in ‘CMOS’ (Complementary Metal-Oxide-Semiconductor). The ‘complementary’ term refers to the use of two ‘complementary’ transistors, one n channel and the other p channel. One of their chief advantages is their low power consumption. It is assumed that students have studied logic gates previously. Otherwise the instructor will need to add an introduction to this topic. The second circuit demonstrates the use of a MOSFET to generate a logic function. The student investigates its performance and should decide after processing the results that it is a NOR function. The challenge is to modify the circuit to generate the OR function. One way to do this is to move the 10kΩ resistor to pull the gate up to 6V, reverse the diodes and connect the switches between them and 0V. The ‘For your records’ section requires students to have access to the data sheet for the `RFP30N06LE` MOSFET. These are available from the Fairchild Semiconductor website. They use the data to perform a power calculation.	**30-45 mins**

Worksheet	Notes for the Instructor	Timing
14 CP4403-TN4	The course finishes with two open-ended assignments, one to create a MOSFET amplifier and the other a source follower. The introduction revisits some of the advantages of MOSFETs over BJTs. It should be stressed that these are application dependent. There are situations where MOSFETs are better and others where BJTs are better. The two investigations use skills practices in earlier worksheets - a detailed plan, correct layout design, use of signal generator and oscilloscope, logical record of results etc. The instructor may require that students submit these before carrying out the practical work. The 'So what' section describes aspects of the way the circuits operate and offers some hints on how to proceed. Recognising that MOSFET parameters can vary widely from device to device, the challenge to students is to 'customise' the circuit to suit their particular MOSFET and improve the circuit's performance. This requires additional resources, such as resistor and capacitor carriers.	**30-45 mins**

Change log

27 07 23	reissued under new code.
23 11 23	Added student notes, Layouts, answers and many changes
11 03 24	BOM on page 60 updated