



EASA - Electronic Fundamentals 3

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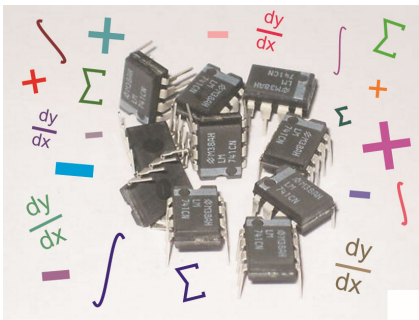
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Developed by Mike Tooley in conjunction with Matrix Technology Solutions

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Worksheet 1

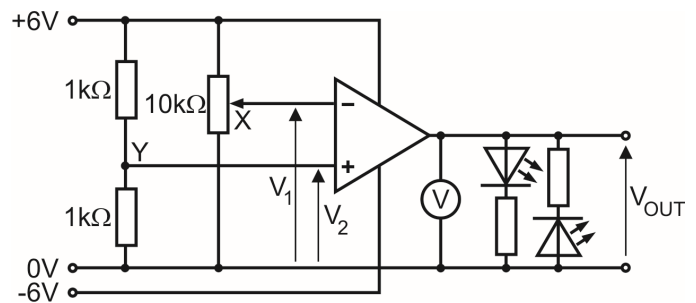
Operational amplifier principles



Operational amplifiers (op-amps) are used in a wide range of avionic applications. In fact, they are the most commonly used analogue IC, used in audio systems and instrumentation systems, used to perform mathematical operations, (hence their name) such as addition, subtraction, and integral and differential calculus. They were at the heart of analogue computing long before digital computers took over.

Over to you:

- This first investigation explores the circuit shown in the diagram opposite. Build this.
- Rotate the knob on the 'pot' from one extreme to the other, and notice what happens to the voltmeter reading as you do so.
- Use a digital multimeter (DMM) set on the 20V DC range to measure the voltage V_2 . Record the value in the table. Its value will be the same on all rows of the table.
- Use the DMM to monitor the voltage V_1 from the 'pot', and set it to the first value, +4.0V, shown in the table.
- Measure the output voltage V_{OUT} . Record its value in the first row of the table.
- Repeat this process for all other values of V_1 given in the table.
- Now swap over the inputs so that the 'pot', output X, provides input V_2 , and the output Y of the voltage divider made from the two 1kΩ resistors, provides input V_1 .
- Repeat the process outlined above, and compare the performance of the op-amp in the two situations.



V_1	V_2	V_{OUT}
+4.0V		
+3.6V		
+3.2V		
+2.8V		
+2.4V		
+2.0V		

V_1	V_2	V_{OUT}
	+4.0V	
	+3.6V	
	+3.2V	
	+2.8V	
	+2.4V	
	+2.0V	

Worksheet 1

Operational amplifier principles



So what?

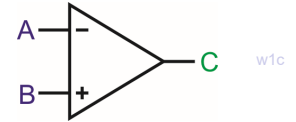
The op-amp has two inputs, **A** and **B**, with a '+' and a '-' sign, and one output terminal **C**.

The circuit symbol is shown opposite.

(The '+' and '-' have nothing to do with the power supply!)

Input **A**, with the '-' sign, is called the **inverting** input.

Input **B**, with the '+' sign, is called the **non-inverting** input.



Op-amps are **high gain differential voltage** amplifiers.

- Voltage **gain** shows how many **times** the output voltage V_{OUT} is bigger than the input V_{IN} .
In general: Voltage **gain** $A = V_{OUT} / V_{IN}$
- A **differential voltage** amplifier amplifies the **difference** in the input voltages.
- For example, when a voltage, V_2 , of $10\mu V$ is applied to input B and a voltage, V_1 , of $7\mu V$ to input A, then the amplifier would amplify the **difference**, $3\mu V$.

The **basic equation** for the op-amp is:

$$V_{OUT} = A_0 \times (V_2 - V_1)$$

A_0 is called the **open-loop voltage gain**, as there is no 'loop' between output and input.

Op-amps have a **high gain**, with A_0 typically $\sim 100,000$, so that the output voltage is typically 100,000 times bigger than the input voltage **difference**. When the difference is $3\mu V$, the output voltage is $300,000\mu V (= 0.3V)$.

Op-amps can't solve the energy crisis. We can't apply a voltage difference of 1V at the inputs and hope to get 100,000V at the output! The equation is true only when the output voltage is between the power supply voltages - in this case +6V and -6V. When V_{OUT} reaches these limits, we say that it is **saturated**. In worksheet 1, the output is always saturated.

When V_2 is bigger than V_1 , the output is as close as it can get to the positive supply voltage, a value known as the positive saturation voltage. When V_1 is bigger than V_2 , the output is close to the negative supply voltage, and is known as the negative saturation voltage.

This circuit is called a **comparator**. It compares the input voltages and shows which is bigger. When V_2 is bigger than V_1 , (i.e. the '+' input voltage is bigger,) V_{OUT} is in **positive** saturation. When V_1 is bigger than V_2 , (i.e. the '-' input voltage is bigger,) V_{OUT} is in **negative** saturation.

For your records:

Explain what is meant by:

- high gain differential voltage amplifier
- saturation
- comparator.

Worksheet 2

Comparator vs Schmitt trigger

Control systems of all kinds rely on sensors to tell them what is happening.

Many of these offer simple digital outputs - either 'on' or 'off'. Some sensors are analogue devices, where, for example, the output of the sensor changes with temperature.

The operational amplifier comparator circuit converts these analogue signals to digital.

In some cases, we need to avoid 'chatter' where the digital output keeps switching from one value to the other rapidly. One solution is to use a Schmitt trigger circuit.

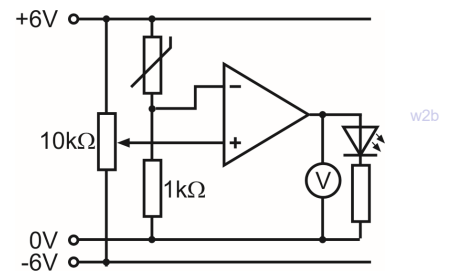


Over to you:

1. The comparator:

We will use a temperature-sensing unit (analogue) to warn when the sensor gets too cold.

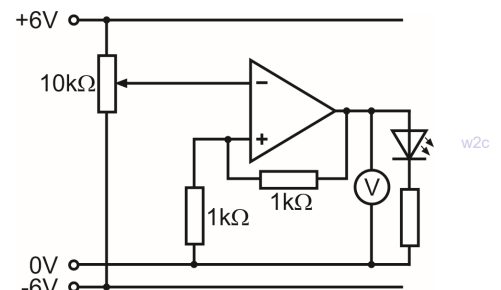
- Set up the circuit shown.
- Turn the knob on the 'pot'. The LED will light at some point. Turn the 'pot' back until the LED is only just lit.
- Now warm up the thermistor between your fingers. The LED should go out.
- Let it cool down again. When it gets cold enough, the LED will light to warn that the temperature has fallen.
- You should find that there is a well-defined 'turn-on' point, controlled by the signal from the 'pot'. The LED is either on or off - the output is digital. There is only one threshold - the LED switches on and off at virtually the same voltage.



2. The Schmitt trigger:

The comparator has only one threshold. If the signal from the sensor sits very close to that threshold and wobbles up and down a little, then the LED can flash on and off unnecessarily. The next circuit avoids that by introducing some 'hysteresis'.

- Set up the circuit shown.
- To simplify the investigation, the temperature-sensing unit has been replaced by a 'pot'.
- The 'pot' now acts as the sensor. Turn it until the LED lights.
- Now turn the 'pot' back until the LED turns off.
- You should find that there are now two thresholds. The LED turns on at one voltage, and off at another. This resolves the issue about unnecessary switching.



Worksheet 2

Comparator vs Schmitt trigger

So what?

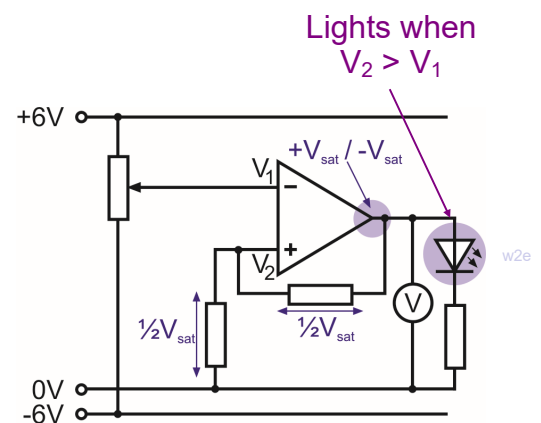
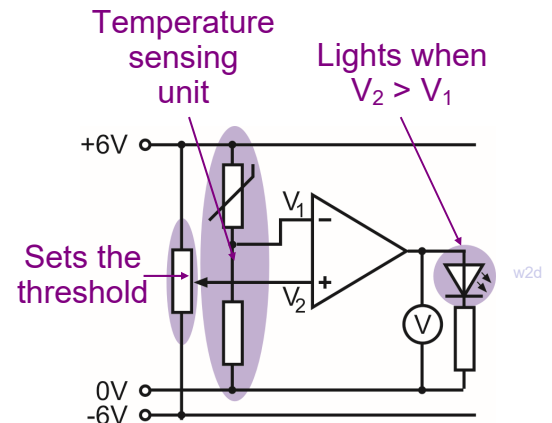
The comparator is the easier circuit to design and use.

- The LED switches on and off at the same threshold voltage, V_2 , set by the 'pot'.
- The temperature-sensing unit (TSU) consists of a thermistor and a fixed resistor.
- As the temperature falls, the thermistor resistance rises, and so the TSU output voltage, V_1 , falls.
- When V_1 falls below the value of V_2 , the LED switches on. (This result was obtained in worksheet 1.)

Near the switching threshold, any electrical noise could push the signal over the threshold, and cause the output to switch rapidly on and off, from the noise alone. Then, it may be better to use a Schmitt trigger circuit.

The behaviour of the op-amp is unchanged:

- When V_2 is bigger than V_1 , the LED is on.
- When V_1 is bigger than V_2 , the LED is off.
- The output of the op-amp sits at either $+V_{sat}$ (positive saturation) or $-V_{sat}$ (negative saturation.)
- The two equal ($1k\Omega$) resistors are connected in series between the output and 0V and so each has a voltage drop of $\frac{1}{2}V_{sat}$ across it. Hence $V_2 = \frac{1}{2}V_{sat}$.
- For example, ideally the output of the op-amp should saturate at +6V and -6V. This means that V_2 is either +3V or -3V.
 - When the LED is off, the op-amp output is -6V, and $V_2 = -3V$. The input signal, V_1 must fall below -3V to switch the LED on.
 - When the LED is on, the output of the op-amp is +6V, and $V_2 = +3V$. The input signal, V_1 must rise above +3V to switch the LED off.
 - There are now **two** switching thresholds.



For your records:

- Draw the circuit diagram to show a temperature-sensing unit connected to :
 - a comparator circuit;
 - a Schmitt trigger circuit. (You will have to modify the one given above!)
- Write a clear explanation in no more than 50 words on the difference between comparators and Schmitt triggers.
- Design a Schmitt trigger circuit like the one above but which has switching thresholds of +2V and -2V. Assume that the saturation voltages are +6V and -6V.

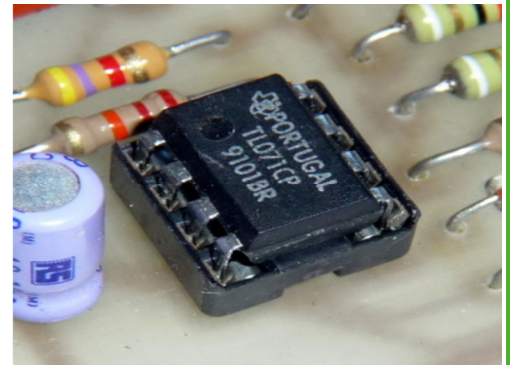
Worksheet 3

Non-inverting amplifier

Avionic systems need careful design. It's not enough to design each stage as a separate system. Each stage must 'talk' effectively to the next, i.e. must transfer its signal without loss or distortion.

The operational amplifier has a number of roles in this. Designed properly, the non-inverting amplifier draws very little current from the input subsystem that supplies it with a signal, an important element of the design.

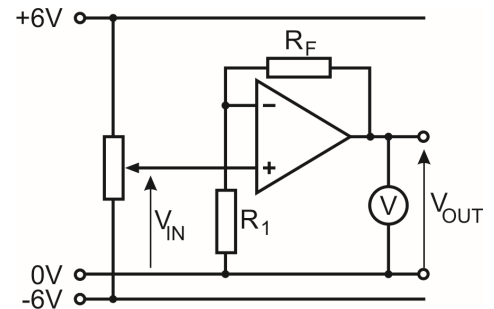
In this worksheet you investigate the gain of a non-inverting amplifier stage.



Over to you:

- This investigation uses the circuit shown opposite. Build this, using a value of $1\text{k}\Omega$ for R_F and $1\text{k}\Omega$ for R_1 . Use a $10\text{k}\Omega$ 'pot' as the input device, as before. Be careful to connect up the power supply correctly. The $+6\text{V}$ power rail is connected to the 'pot', and also provides power to the op-amp, though this is not shown in the circuit diagram. Similarly the -6V power rail is connected to the 'pot', and also provides power to the op-amp.
- Use a digital multimeter (DMM) set on the 20V DC range to monitor the voltage V_{IN} . Turn the 'pot' to set this voltage to $+2.5\text{V}$.
- Measure the output voltage V_{OUT} and record its value in the first row of the table.
- Repeat this process for all the other values of V_{IN} .
- Calculate the gain using the formula:

$$\text{Voltage gain} = V_{\text{OUT}} / V_{\text{IN}}$$
 Use your results to complete the third column.
- Now swap the $1\text{k}\Omega$ feedback resistor for a $10\text{k}\Omega$ resistor.
- Repeat the process outlined above, using the new values of V_{IN} given in the second table.
- Complete the second table in the same way as before.



$R_F = 1\text{k}\Omega, R_1 = 1\text{k}\Omega$		
V_{IN}	V_{OUT}	Gain
$+2.5\text{V}$		
$+1.5\text{V}$		
$+0.5\text{V}$		
-0.5V		
-1.5V		
-2.5V		

$R_F = 10\text{k}\Omega, R_1 = 1\text{k}\Omega$		
V_{IN}	V_{OUT}	Gain
$+0.5\text{V}$		
$+0.3\text{V}$		
$+0.1\text{V}$		
-0.1V		
-0.3V		
-0.5V		

Worksheet 3

Non-inverting amplifier



So what?

The industry standard op-amp is the '741', produced by Fairchild Semiconductors in 1968. Since then, many improvements have been made to the performance.

The ideal characteristics of an op-amp are:

- infinite open-loop voltage gain;
- infinite bandwidth, (the range of frequencies amplified successfully;)
- infinite input impedance, (draws no current from the device creating its input signal;)
- infinite slew-rate, (the output voltage can leap instantly to any value;)
- zero output impedance, (delivers the full output voltage to any subsystem that follows;)
- infinite common-mode rejection ratio (CMRR) (amplifies only the difference in voltage between the inputs and ignores any voltage common to both, such as interference.)

Often, subsystems delivering a signal to an amplifier, such as a microphone, cannot provide much current. If the amplifier draws significant current from it, then the signal voltage falls, defeating the point of using an amplifier. The non-inverting amplifier, however, offers a very high input impedance, typically $1M\Omega$, so that it draws very little current from its signal source.

The theoretical value for the voltage gain is given by the formula:

$$\text{Voltage gain} = 1 + R_F / R_1$$

For the first part of the investigation, where $R_F = 1k\Omega$ and $R_1 = 1k\Omega$, this gives a value:

$$\text{Voltage gain} = 1 + 1 / 1 = 2$$

(Using any two equal valued resistors would give the same voltage gain. Using high values reduces battery drain and power dissipation.)

For the second part, where $R_F = 10k\Omega$ and $R_1 = 1k\Omega$, this gives a value:

$$\text{Voltage gain} = 1 + 10 / 1 = 11.$$

- Look at your measurements. Do they support these values of voltage gain?
- Replace the 'pot' with a signal generator, set to output sine waves with an amplitude of 100mV at a frequency of 1kHz. Use an oscilloscope to measure the amplitude of the input and output signals, and hence measure the AC voltage gain.

For your records:

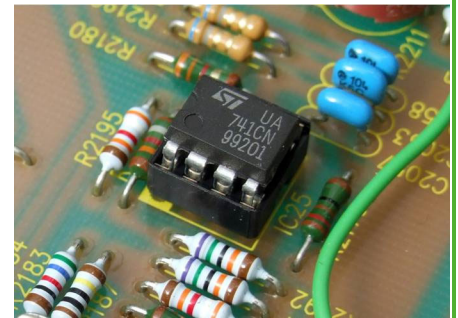
Complete the following table:

Input voltage	Output voltage	Voltage gain	Resistor R_F	Resistor R_1
5mV			10k Ω	2k2 Ω
	300mV	15		1k Ω
20mV	400mV		10k Ω	
10mV		10		10k Ω
3mV	18mV		100k Ω	

Worksheet 4

Voltage follower

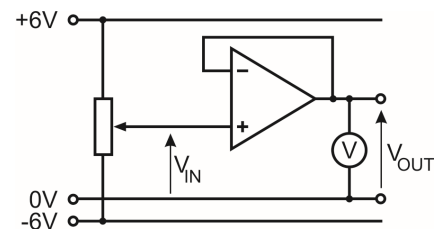
The voltage follower, or buffer, provides no voltage gain but offers the significant advantage that it draws very little current from the signal source. As such, it is an extreme form of a non-inverting amplifier that uses zero ohms as the feedback resistor and infinite ohms as resistor R_1 . This produces a voltage gain of unity (i.e. 1). In other words the circuit behaves like a direct wire connection but with hardly any current flowing in it!



Over to you:

1. Behaves like a length of wire:

- Set up the first circuit.
Use a $10\text{k}\Omega$ 'pot' as the input device, as before.
Take care with the power connections!
- Notice the connecting link between output and inverting input. This provides the 100% feedback.
- Use a digital multimeter (DMM) to monitor the voltage V_{IN} .
Turn the 'pot' to set this voltage to $+2.5\text{V}$.
- Measure the output voltage V_{OUT} and record it in the table.
- Repeat this process for all the other values of V_{IN} .

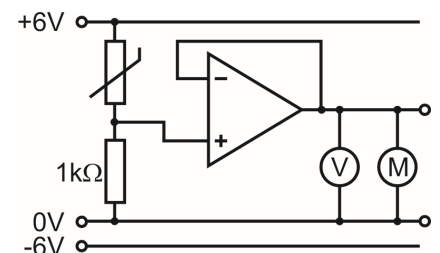
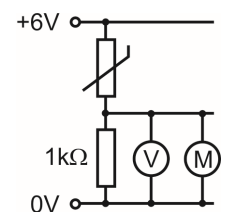


V_{IN}	V_{OUT}
$+2.5\text{V}$	
$+1.5\text{V}$	
$+0.5\text{V}$	
-0.5V	
-1.5V	
-2.5V	

2. The magic bit:

The plan is to use a temperature sensor to operate a fan.
The hotter the room, the faster the fan.

- Set up the second circuit.
- When you test this, you will find that it does not work!
- Disconnect the motor. The voltmeter shows a healthy reading, which rises when the temperature increases.
- Re-connect the motor and this reading falls to nearly zero.
- Now set up the third circuit and test it.
(Notice the 100% feedback!) The motor affects the output voltage, but nowhere near as much. This version works!



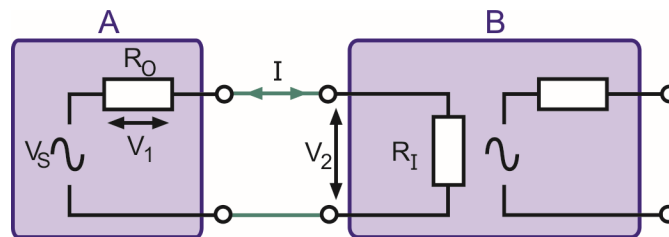
Worksheet 4

Voltage follower

So what?

Matching for voltage transfer:

No matter how complex its inner workings, we can picture an electronic subsystem as a voltage source, V_S , in series with an output resistance, R_O .



The diagram shows two subsystems, **A** and **B**. Our design aim is to pass on as much of the voltage V_S as possible. In other words, we want V_2 , the voltage 'seen' by **B**, to be as close as possible to V_S , the voltage generated by **A**.

Now $V_2 + V_1 = V_S$, so we want to make V_1 as small as possible, by making the current I as small as possible. In turn, this means that the input resistance of **B**, R_I , must be much bigger than R_O , the output resistance of **A**.

The non-inverting amplifier has an input resistance of at least 1 M Ω . (Different op-amps have different input impedances. The TL081 used in the Locktronics op-amp carrier has an input resistance of 1 million M Ω .) As a result, the current drawn from the input signal source is very small, and the loss of signal (V_1 in the diagram,) is small.

As a result, when connected to the temperature sensing unit, in part 2 of the investigation, the voltage follower has very little effect on the output of the sensor. The voltage from the sensing unit is conveyed with little change to the output of the follower. The motor now draws current from the op-amp, and not from the sensing unit.

For your records:

- Complete the following:
 - In a voltage follower, the output voltage is to the input voltage. However, the input impedance (resistance) of the voltage follower is so big that it draws current from the input signal source. As a result, it has little or no effect on the input signal. The output device draws current from the op-amp and not from the signal source.
- Use the internet to research the following terms and explain each in less than 25 words:
 - buffer;
 - 100% feedback;
 - equivalent circuit.

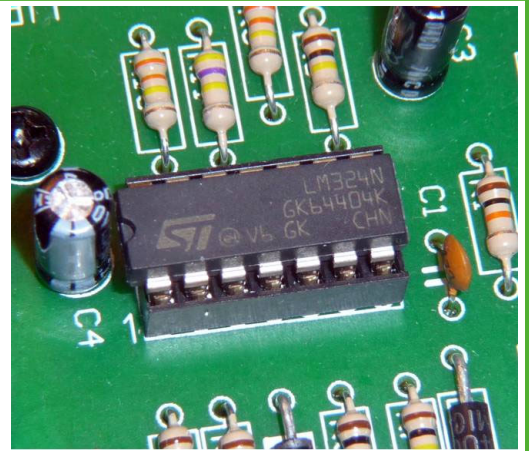
Worksheet 5

Inverting amplifier

The inverting amplifier is somewhat inferior as a voltage amplifier, but leads to a number of exciting applications based on this circuit.

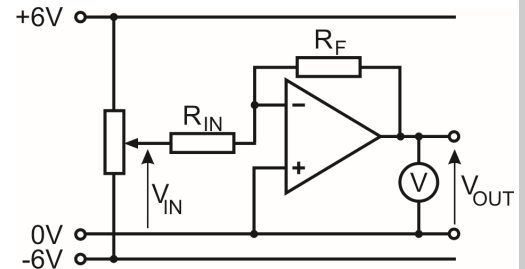
The fact that it inverts the signal is rarely significant - an audio signal sounds just the same whether or not it is inverted!

More importantly, the inverting amplifier usually draws more current from its signal source, than does the non-inverting amplifier, and so needs careful design.



Over to you:

- The next investigation uses the circuit shown opposite. Build this, using a value of $10\text{k}\Omega$ for R_F and $10\text{k}\Omega$ for R_{IN} . Use a $10\text{k}\Omega$ 'pot' as the input device, as before. Be careful to connect up the power supply correctly! The $+6\text{V}$ power rail is connected to the 'pot', and also provides power to the op-amp. Similarly the -6V power rail is connected to the 'pot', and to the op-amp.



- Use a digital multimeter (DMM) to monitor the input voltage V_{IN} . Turn the 'pot' to set this to $+2.5\text{V}$.
- Measure the output voltage V_{OUT} and record it in the first row of the table.
- Repeat this process for all the other values of V_{IN} .
- Calculate the voltage gain using the formula:

$$\text{Voltage gain} = V_{OUT} / V_{IN}$$
 and hence complete the third column.

$R_F = 10\text{k}\Omega, R_{IN} = 10\text{k}\Omega$		
V_{IN}	V_{OUT}	Gain
$+2.5\text{V}$		
$+1.5\text{V}$		
$+0.5\text{V}$		
-0.5V		
-1.5V		
-2.5V		

- Now swap the $10\text{k}\Omega$ input resistor for a $1\text{k}\Omega$ resistor.
- Repeat the same process, using the values of V_{IN} given in the second table.
- Complete the second table in the same way as before.
- The formula for the voltage gain is simpler than for the non-inverting amplifier. How could you use a $10\text{k}\Omega$ resistor and two $1\text{k}\Omega$ resistors to give you a voltage gain of 5? Test your idea by modifying the circuit you used above.

$R_F = 10\text{k}\Omega, R_{IN} = 1\text{k}\Omega$		
V_{IN}	V_{OUT}	Gain
$+0.5\text{V}$		
$+0.3\text{V}$		
$+0.1\text{V}$		
-0.1V		
-0.3V		
-0.5V		

Worksheet 5

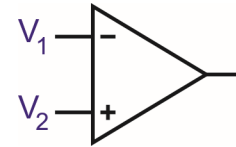
Inverting amplifier

So what?

A significant result :

$$V_2 = V_1$$

in any op-amp circuit where the output is not saturated.



w5c

The reason:

- The output voltage is never very large, say 10V maximum.
- Provided that the output is not saturated, $V_{OUT} = A_o \times (V_2 - V_1)$.
- Open loop gain, A_o , is around 100,000.
- Hence, $10 = 100,000 \times (V_2 - V_1)$, so $(V_2 - V_1) \sim 0.0001V$, or, to a good approximation:
 $V_2 = V_1$

In the case of the inverting amplifier, $V_2 = 0V$, because it is connected directly to it.

As long as the output is not saturated, $V_1 = 0V$ also. This can be a good experimental check that the op-amp is working correctly.

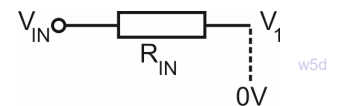
For the inverting amplifier:

$$\text{Voltage gain} = - R_F / R_{IN}$$

As a result:

- when $R_F = R_{IN}$, the voltage gain = -1;
- when $R_F = 10 \times R_{IN}$, the voltage gain = -10, and so on.

However, because $V_1 = 0V$ when the output is not saturated, (and amplifiers should never be driven into saturation,) the input source sees the amplifier as the input resistor connected to 0V, as the diagram shows.



w5d

The value of R_{IN} should be kept large in order to limit the current that the amplifier draws from the input source. It should be at least 1k Ω , and preferably bigger than 10k Ω .

- Replace the 'pot' with a signal generator, set to output sine waves with an amplitude of 100mV at a frequency of 1kHz. Use an oscilloscope to measure the amplitude of the input and output signals, and hence measure the AC voltage gain.

For your records:

Complete following table :

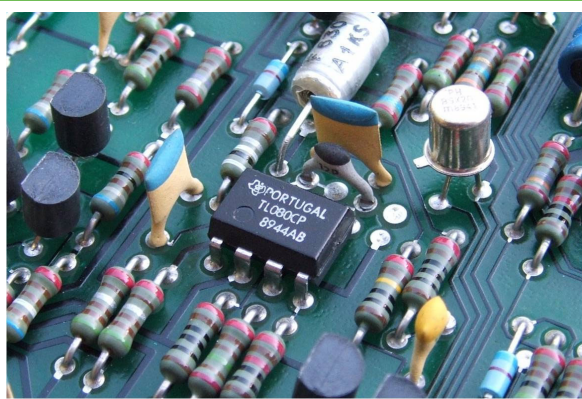
Input voltage	Output voltage	Voltage gain	Resistor R_F	Resistor R_{IN}
5mV			20k Ω	2k Ω
	-300mV	12		10k Ω
20mV	100mV		100k Ω	
-10mV		3		10k Ω
3mV	-24mV		240k Ω	

Worksheet 6

Summing amplifier

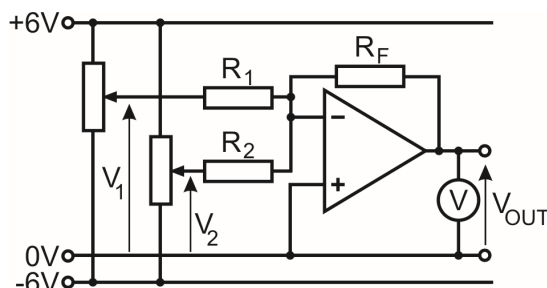
The inverting amplifier has only one input. However, we can add other inputs in such a way that each operates independently, with the result that the output voltage is the sum of the individual inputs. This allows us to combine signals from a number of different transducers or signal sources.

In this worksheet you investigate a simple summing amplifier with only two inputs.



Over to you:

- The next circuit is a modification of that used in the previous worksheet. It is shown opposite.
- Build this, using $10\text{k}\Omega$ resistors for R_F , R_1 and R_2 . Take care with the power connections!
- Use a DMM to monitor the input voltages V_1 and V_2 , set on two $10\text{k}\Omega$ pots. Set their values to those given in the first line of the table.
- Measure the output voltage V_{OUT} and record it in the first row of the table.
- Repeat this process for all the other values of input voltages.



$R_F = R_2 = R_1 = 10\text{k}\Omega$		
V_2	V_1	V_{OUT}
+2.0V	+1.0V	
+1.5V	+1.0V	
+0.5V	-0.5V	
-0.5V	-0.5V	
-1.5V	+2.0V	
-2.5V	+2.0V	

- Now swap the $10\text{k}\Omega$ feedback resistor for a $1\text{k}\Omega$ resistor.
- Use the same process as before to investigate this circuit.
- Record your results in the second table.

$R_F = 1\text{k}\Omega$ $R_2 = R_1 = 10\text{k}\Omega$		
V_2	V_1	V_{OUT}
+2.0V	+1.0V	
+1.5V	+1.0V	
+0.5V	-0.5V	
-0.5V	-0.5V	
-1.5V	+2.0V	
-2.5V	+2.0V	

Worksheet 6

Summing amplifier



So what?

A significant result :

$$V_{\text{OUT}} = - \left[\left(\frac{R_F}{R_1} \times V_1 \right) + \left(\frac{R_F}{R_2} \times V_2 \right) \right]$$

and when $R_F = R_1 = R_2$ we have:

$$V_{\text{OUT}} = - (V_1 + V_2)$$

The minus sign results from the inverting amplifier.

Recall that for a simple inverting amplifier with only one input:

$$\text{Voltage gain} = - R_F / R_{\text{IN}}$$

For your records:

- Complete the following table:

Input voltage V_1	Resistor R_1	Input voltage V_2	Resistor R_2	Resistor R_F	Output voltage V_{OUT}
150 mV	2 k Ω	350 mV	2k Ω	10 k Ω	
	100 k Ω	1 V	50 k Ω	100 k Ω	-1 V
200 mV	50 k Ω	500 mV	100 k Ω	100 k Ω	
-10 mV	2.5 k Ω		2.5 k Ω	10 k Ω	0 V
300 mV	1 k Ω	-90 mV		1.2 k Ω	150 mV

Worksheet 7

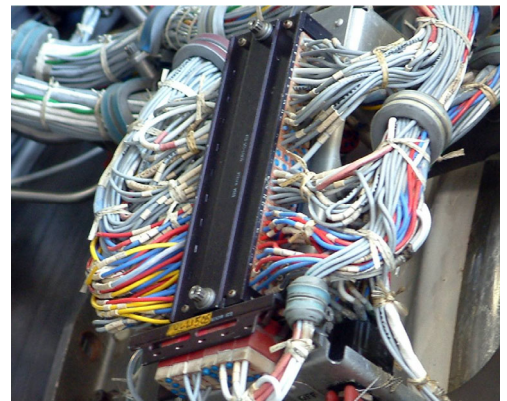
Differential amplifiers

Most avionic op-amp applications are found in control and instrumentation systems of one kind or another.

The differential amplifier has application to many of these systems and its name gives a clue as to what it does.

Its importance lies in the ability to distinguish between background components to a signal, such as temperature and power supply voltage, and the true signal.

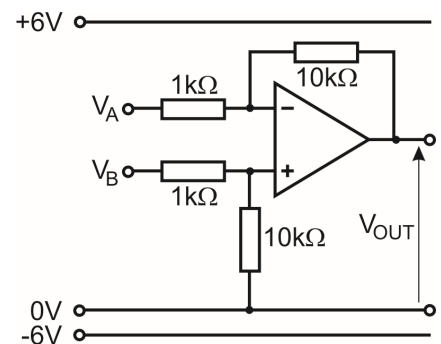
It is often used in conjunction with bridge circuits, to monitor, for example, strain in aircraft structures, such as fuselages and wings.



w7a

Over to you:

- The next circuit is another modification of the inverting amplifier used earlier. It is shown opposite.
- Build this, using two $10\text{k}\Omega$ resistors and two $1\text{k}\Omega$ resistors. Use two $10\text{k}\Omega$ 'pots' to provide the input signals, V_A and V_B . Notice the symmetry of the arrangement. The two input resistors are equal. The inverting input is connected through a $10\text{k}\Omega$ resistor to the output. The non-inverting input is connected through a $10\text{k}\Omega$ resistor to 0V .
- Use a DMM to monitor the input voltages V_A and V_B . Set their values to those given in the first line of the table.
- Measure the output voltage V_{OUT} and record it in the first row of the table.
- Repeat this process for all the other values of input voltages. As with all amplifier circuits, it is important to avoid output saturation. **Watch out for this in your results!**
- Analyse your results.
Can you see the pattern that links V_{OUT} to V_A and V_B ?
Test your theories by trying other combinations of input voltages, and predicting the result.



w7b

V_B	V_A	V_{OUT}
+2.0V	+1.8V	
+1.5V	+1.2V	
+0.4V	0V	
0V	-0.2V	
-1.5V	-1.3V	
-2.2V	-2.6V	

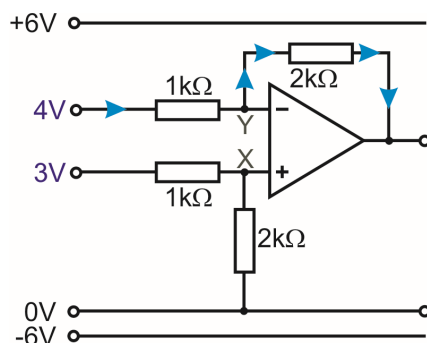
Worksheet 7

Differential amplifiers

So what?

Here is an analysis of the performance of the differential amplifier.

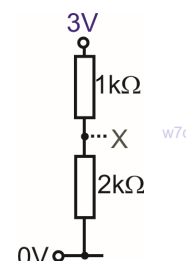
(The values of the resistors have been changed to make the arithmetic easier.)



Earlier we pointed out that the ideal op-amp has infinite input impedance, and so draws no current from its input source. We will assume that the op-amp used here is ideal!

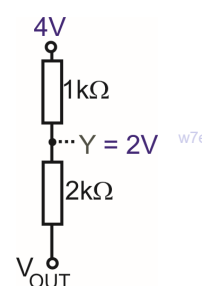
Look at point X, the non-inverting input of the op-amp. It is at the centre of a voltage divider. We can draw it as shown opposite:

There is a 3V drop across two resistors, one of which is twice as big as the other. As a result, the 2kΩ resistor takes twice as much of the voltage as does the 1kΩ resistor, giving 2V across the 2kΩ resistor and 1V across the 1kΩ resistor. In other words, point X sits at 2V.



Assuming that the output of the op-amp is not saturated, the two inputs must sit at the same voltage (as we pointed out earlier.) In other words, point Y sits at 2V too.

The output of the op-amp can be viewed as part of a voltage divider. The 1kΩ input resistor has a 2V drop across it (from 4V at the input to 2V at point Y.) The 2kΩ resistor in series with it must have twice as big a voltage drop, i.e. 4V.



Looking at the blue current arrows on the diagram, current flows from point Y to the output. That means that the output is at a lower voltage than point Y, in this case 4V lower. As Y is at 2V, the output must be at $(2 - 4) = -2V$.

For your records:

Calculate the output voltage if all four resistors in the circuit have a resistance of 10kΩ and the input voltages are:

$$V_A = +6V$$

$$V_B = +4V$$

Show how you obtain your answer.

Worksheet 8

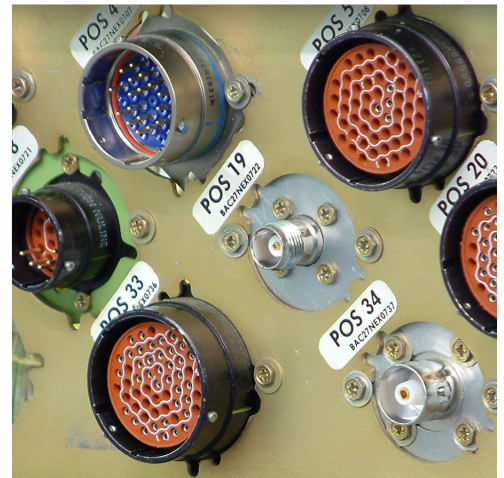
Differentiator

A differentiator produces an output voltage that represents the rate of change of its input. This simply means that, if the input voltage remains constant (i.e. isn't changing,) the output voltage also remains constant.

If the input voltage changes, the output voltage takes a value that is proportional to the **rate** at which the input is changing. The faster the input voltage changes, the greater will be the output ,

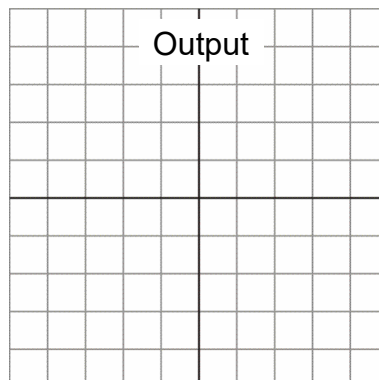
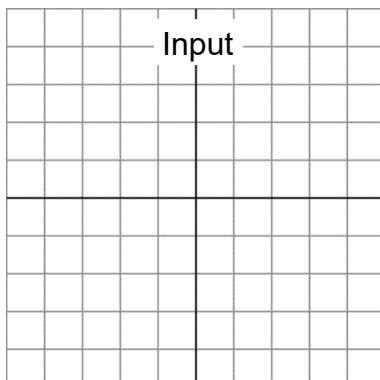
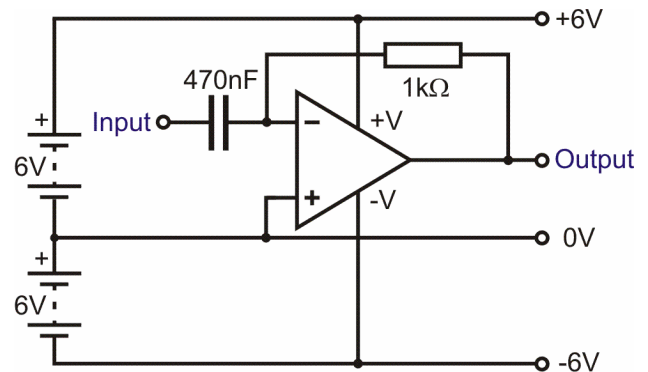
In mathematics this is equivalent to the differential function.

In this worksheet, you investigate the an operational amplifier differentiator, supplied with a square wave input. This waveform is used because the steeply rising and falling edges exhibit a very rapid rate of change whilst the mark and space,



Over to you:

- Build the differentiator circuit shown opposite. Use two DC power supplies, set to 6V, plugged into the dual-rail power supply carrier, to supply the +6V / 0V / -6V power rails.
- Connect the input to a signal generator, set to output 1V peak-to-peak at a frequency of 100Hz.
- Connect a dual trace oscilloscope so that channel A displays the input and channel B the output waveforms of the differentiator. Connect the ground terminals to the 0V supply rail.
- Adjust the oscilloscope controls to display two cycles of the input and output waveforms.
- Sketch these on the grids provided and label the voltage and time axes.



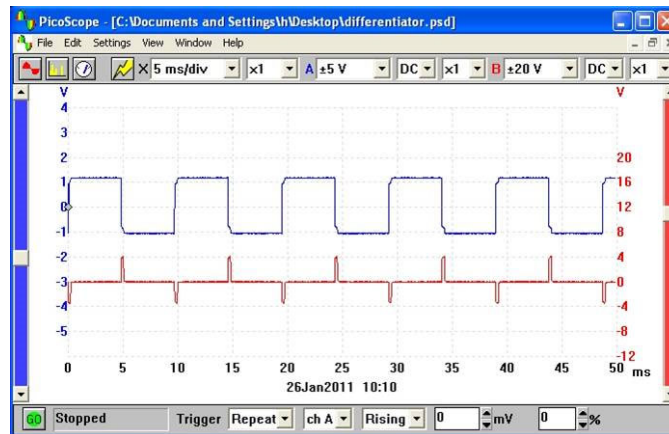
Worksheet 8

Differentiators



So what?

A typical set of waveforms is shown in the picture.



A significant point!

Notice that the **negative** going 'spikes' on the output waveform occur on the fast **rising** edge of the square waveform whereas the **positive** going 'spikes' occur on the fast **falling** edge of the square waveform.

The output of the differentiator is thus the inverse of the differential of its input function. Expressed in mathematical terms the output voltage is given by:

In other words the output is the $V_{OUT} \propto -\frac{d(V_{IN})}{dt}$ derivative function of the input.

The performance of the differentiator (and its ability to produce an accurate differential function) is determined primarily by the ratio of the time constant of the RC network to the periodic time of the input function.

For accurate differentiation the periodic time, t , needs to be very much larger than the time constant, RC (typically at least ten times larger).

Calculate the ratio of t to RC used in this circuit:

$$\text{Ratio, } \frac{t}{CR} =$$

For your records:

Investigate what happens when you change the type of input signal. For example, input a 100Hz sine wave, and, if your signal generator provides it, a 100Hz triangular wave.

Worksheet 9

Integrator

An integrator provides the opposite function to that of a differentiator.

Its output is equivalent to the area under the graph of the input function rather than its rate of change.

If the input remains constant (and is other than 0V,) the output voltage will ramp up or down according to the polarity of the input.

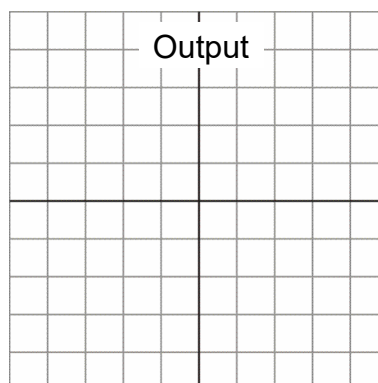
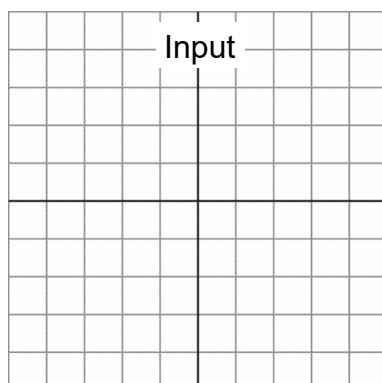
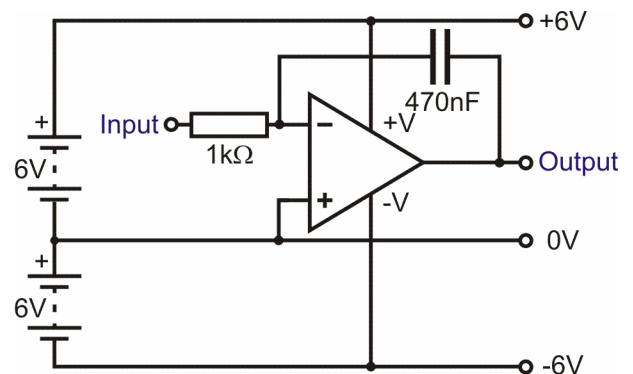
The longer the input voltage remains at a particular value, the larger the output voltage.

In this worksheet, you investigate the an operational amplifier integrator, supplied with a square wave input.



Over to you:

- Build the integrator circuit shown opposite. Once again, you will need to use two DC power supplies, set to 6V, plugged into the dual-rail power supply carrier, to supply the +6V / 0V / -6V power rails.
- Connect the input to a signal generator, set to output 1V peak-to-peak at a frequency of 100Hz.
- Connect a dual trace oscilloscope so that channel A displays the input and channel B the output waveforms of the integrator. Connect the ground terminals to the 0V supply rail.
- Adjust the oscilloscope controls to display two cycles of the input and output waveforms.
- Sketch these on the grids provided and label the voltage and time axes.



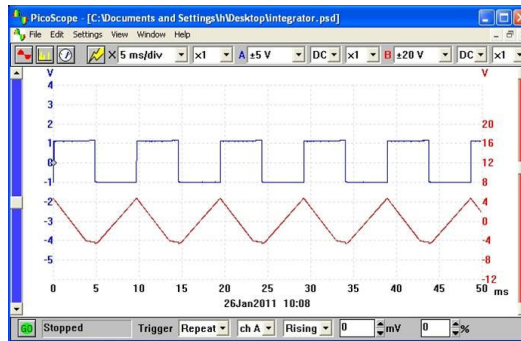
Worksheet 9

Integrators



So what?

A typical set of waveforms is shown in the picture.



Yet another important point!

Notice that the output waveform ramps **down** when the input voltage is held **high** and ramps **up** when the input voltage is held **low**.

The output of the integrator is thus the inverse of the integral of its input function.

Expressed in mathematical terms the output voltage is given by:

$$V_{OUT} \propto -\int V_{IN} dt$$

In other words the output is the integral function of the input.

As with the differentiator, the performance of the integrator (and its ability to produce an accurate integral function) is determined primarily by the ratio of the time constant of the C-R network to the periodic time of the input function. (The other way up this time!)

For accurate integration the time constant, RC, should be very much larger than periodic time, t (typically at least ten times larger).

Calculate the ratio of RC to t used in this circuit.

$$\text{Ratio, } \frac{CR}{t} =$$

For your records:

- Once again, investigate the effect of changing the type of input signal, using a 100Hz sine wave, and, if your signal generator provides it, a 100Hz triangular wave, for example.
- Investigate the effect on the output waveform of changing the frequency of the input signal.

Worksheet 10

Logic gates



Logic gates are one of the commonest digital integrated circuits. They perform logic functions, such as NOT, AND and OR. This worksheet looks at the simplest of these, the NOT function. This could be used to warn when an undercarriage door is NOT closed, for example.

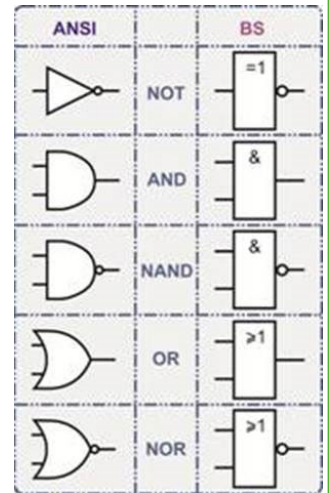
Logic gates can be built in a variety of ways, resulting in a number of logic 'families,' each with its own capabilities and limitations. One of these is called **CMOS**.

The photograph shows a CMOS NOT gate, identified by '4049'. It is

known as a 'hex inverting buffer.' (Hex = 6, inverting = NOT, buffer = able to deliver a ~ milliamps of current) meaning that the IC has six NOT gates, each with some current capability.

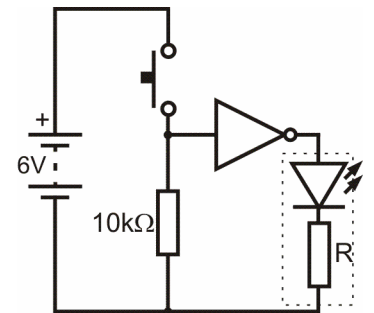


Like all electronic devices, logic gates are represented by circuit symbols, but there several versions of them. The common ones are 'ANSI' (American National Standards Institute) and 'BS' (British Standard) also called 'SB' (System Block) symbols. Both are given in the diagram opposite but aircraft schematics invariably use the ANSI symbols.



Over to you:

- Build the circuit shown opposite. Notice the LED connected between the output of the NOT gate and 0V. This is in addition to the LED built into the NOT gate carrier itself.
- Set the DC power supply to 6V.
- With the multimeter on the 20V DC range, measure the voltages at the input and then output of the NOT gate when the switch is turned off (open.)
- Record both readings in the first table.
- Note whether the external LED is on or off.
- Now close the switch, and repeat the measurements. Record them in the first table.
- Invert the switch unit, by swapping over the switch and 10kΩ resistor. Repeat the measurements and record them in the second table.



Switch unit	Input voltage	Output voltage	State of LED
Open (off)			
Closed (on)			

Switch unit inverted	Input voltage	Output voltage	State of LED
Open (off)			
Closed (on)			

Worksheet 10

Logic gates



So what?

First, a word about logic levels. The voltages you measured are either pretty close to +6V or 0V. For CMOS logic gates, logic 1 is any voltage greater than 70% of the supply voltage, and logic 0 anything less than 30% of supply voltage. In this case, with a 6V power supply, logic 1 is bigger than 4.2V and logic 0 is less than 1.8V.

- Use this information to convert your input and output voltage readings into logic levels. Complete the table, known as the **truth-table**, for the NOT gate, which describes the behaviour of the gate.

NOT gate	
Input	Output
(Logic) 0	
(Logic) 1	

The NOT gate produced the same effect, whether the switch unit was inverted or not. It turned a logic 0 input into a logic 1 output, and vice-versa. The behaviour of the switch unit changed. To begin with, it produced a logic 0 signal when the switch was open, and a logic 1 signal when closed. When inverted, the behaviour inverted so that with the switch open, it generated a logic 1 signal and, with it closed logic 0.

A challenge - Why do we need a resistor in the switch unit? Why not just have the switch?

- See what happens when you remove the resistor from the switch unit.

With the switch between the +6V supply and the input, things seem to behave as before, when the resistor was in place. However, with the switch connected between the input and the 0V connection, nothing happens. The output of the NOT gate always sits at logic 1, regardless of the state of the switch.

CMOS circuitry is wonderful, but it has a weakness - the inputs must not 'float' (be left unconnected). If they are, the outcome is unpredictable. The output can even oscillate so rapidly between logic 0 and logic 1, that the circuit can overheat and be destroyed. Always use a resistor either to 'pull' the input up to logic 1, by connecting it between the positive supply and the input, or 'pull' it down to logic 0, by connecting it between the input and 0V.

The 'Locktronics' NOT gate carrier is wired up so that the input sits at logic 0, when nothing is connected to it.

For your records:

- **A surprise** - we said that a CMOS NOT gate carries the serial number '4049'. Remove the NOT gate carrier, turn it upside down and look at the integrated circuit used in it. The serial number on it is '4011'. Find out what the '4011' chip is.
- **Another challenge** - What happens if you connect the output of one NOT gate to the input of another NOT gate? How does the output of the second NOT gate relate to the input of the first NOT gate? Is this what you would expect?

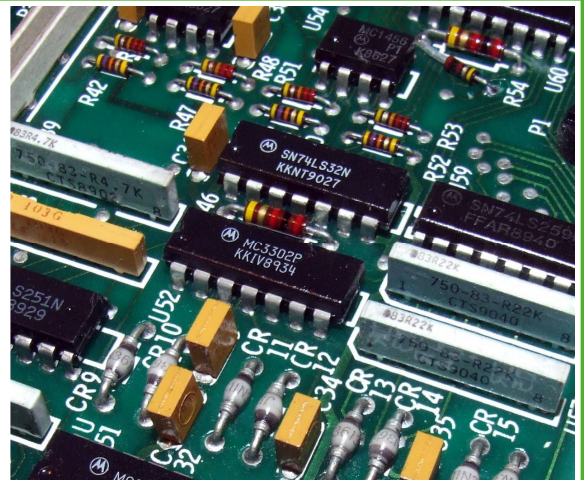
Worksheet 11

AND and OR logic

Often, aircraft systems are designed to operate only when certain criteria are met.

For example, the autopilot will **NOT** operate when the aircraft is on the ground. We could easily implement this logic using the NOT gate that you met in Worksheet 10.

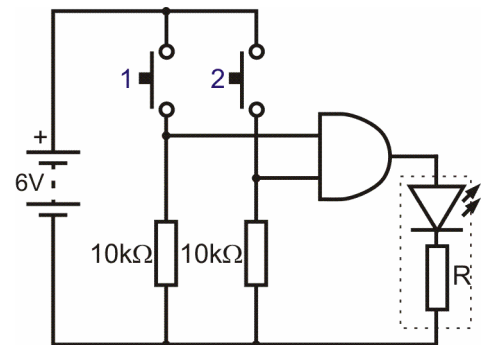
Sometimes, however, several conditions need to be met. We can solve these using combinations of AND logic and OR logic gates. For example, the supply to the igniters of a gas turbine engine should only operate when the engine start switch is operated **AND** the turbine r.p.m. has reached the minimum speed required to maintain combustion.



Over to you:

The AND gate

- Build the circuit shown opposite. Take care to power up the logic gate carrier correctly!
- Set the DC power supply to output 6V.
- Connect a LED between the output of the gate and 0V. (The protective resistor is already connected inside the LED carrier.)
- There are four sets of measurements to make: Firstly, leave both switches open (off).
- With the multimeter on the 20V DC range, measure the voltage at input A, then at input B, and finally at the output of the AND gate. Record your measurements in the first row. Note whether the external LED is on or off.
- Secondly, close switch 1 leaving switch 2 open.
- Repeat the measurements, recording them in the second line of the table.
- Continue in this way to complete the table for the other combinations of switch positions.



Switch 1	Switch 2	Voltage at input A	Voltage at input B	Output voltage	State of LED
Open (off)	Open (off)				
Open (off)	Closed (on)				
Closed (on)	Open (off)				
Closed (on)	Closed (on)				

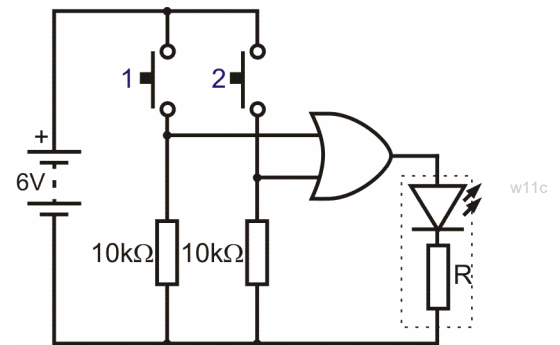
Worksheet 11

AND and OR logic

Over to you:

The OR gate

- Build the circuit shown opposite, with the DC power supply set to output 6V.
- Connect the LED carrier between the output of the OR gate and 0V.
- Follow the same steps as for the AND gate, recording your results in the table.



Switch 1	Switch 2	Voltage at input A	Voltage at input B	Output voltage	State of LED
Open (off)	Open (off)				
Open (off)	Closed (on)				
Closed (on)	Open (off)				
Closed (on)	Closed (on)				

So what?

As before, you used a 6V power supply and so logic 1 is any voltage greater than 4.2V and logic 0 is any voltage less than 1.8V. Use this and your measurements to complete the truth-table for the two types of gate.

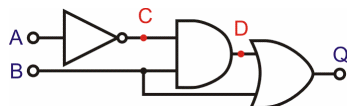
Input A	Input B	AND
0	0	
0	1	
1	0	
1	1	

Input A	Input B	OR
0	0	
0	1	
1	0	
1	1	

The AND and OR logic functions are easy to understand. The output of the AND gate will be logic 1 **only** when input A **AND** input B (**AND** input C etc. if there are more inputs), are all logic 1. The output of the OR gate will be logic 1 when either input A **OR** input B (or both!) inputs are at logic 1. Your results should confirm this behaviour.

For your records:

Work out what happens in the following circuit, and fill in the truth table:



Confirm your ideas by building and testing the logic system.

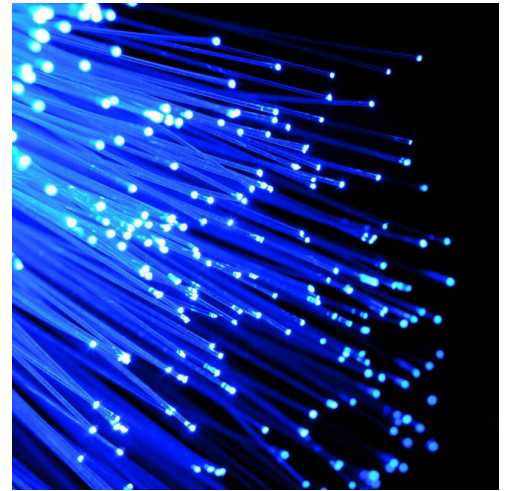
A	B	C	D	Q
0	0			
0	1			
1	0			
1	1			

Worksheet 12

Fibre optics

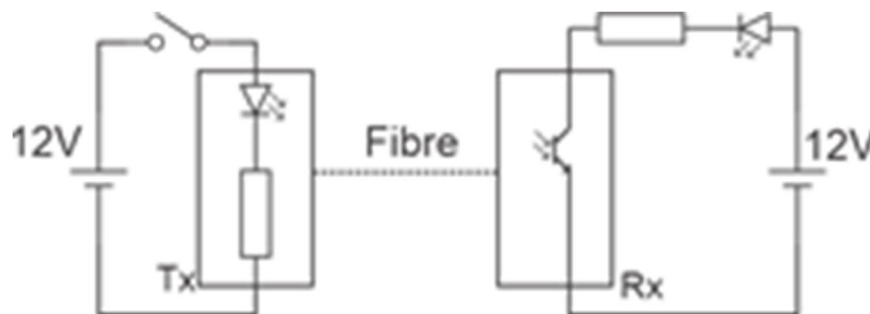
Fibre optics are increasingly used in modern aviation systems because they provide significant advantages over copper in terms of size, weight, bandwidth and immunity to electromagnetic interference. All this means that system designers can now incorporate a range of new aircraft features for operators and consumers.

Photograph shows a number of fibre optic cables with light coming from them.



w11a

Over to you:



- Build the circuit shown above using the Fibre optic Transmitter (Tx) and Receiver (Rx) components. The circuit shows separate 12V power and earth connections to show how fibre optics allow one circuit to be isolated from another - but for expediency you can use the same power supply.
- Make sure that when you close the switch light flows from transmitter to receiver and the LED lights up. Correspondingly the LED goes off when the switch is opened.
- Replace the switch with a push to make and see that the response time is near instantaneous.
- Slowly remove the fibre from the receiver - at what distance from the receiver does the signal stop getting through?

So what?

- Fibre optics offer practical low cost ways of transmitting high bandwidth signals for controlling systems and for media transmission in an aircraft.
- Fibre optics have lots of advantages over copper wires: weight, isolation, electromagnetic interference immunity and bandwidth.

About these questions

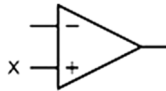
These questions are typical of those that you will be required to answer in the EASA Part-66 examination.

You should allow 15 minutes to answer these questions and then check your answers with those given on page 36.

Please remember that **ALL** these questions must be attempted **without** the use of a calculator and that the pass mark for all Part-66 multiple-choice examinations is 75%!

1. The connection marked 'X' in the diagram is the:

- (a) inverting input
- (b) non-inverting input
- (c) positive supply input.



rq1

2. The typical value of open-loop voltage gain for an operational amplifier is:

- (a) between 10 and 100
- (b) between 100 and 1000
- (c) more than 100,000.

3. In normal operation, the output voltage of a comparator will be at a voltage which is:

- (a) close to zero
- (b) close to either the positive or negative supply voltage
- (c) the same as the input voltage.

4. Operational amplifiers have:

- (a) very high input resistance and very high open-loop voltage gain
- (b) very high input resistance and very low open-loop voltage gain
- (c) very low input resistance and very high open-loop voltage gain.

5. The input resistance of an operational amplifier is typically:

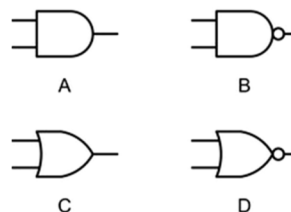
- (a) less than 100 Ω
- (b) between 1 k Ω and 10 k Ω
- (c) more than 1 M Ω .

6. Which of the logic gates shown have inverted outputs?

- (a) A and B
- (b) B and D
- (c) C and D

7. The output resistance of an operational amplifier is typically:

- (a) less than 100 Ω
- (b) between 1 k Ω and 10 k Ω
- (c) more than 1 M Ω .



rq2

8. Which one of the following gives the voltage gain of the operational amplifier circuit shown?

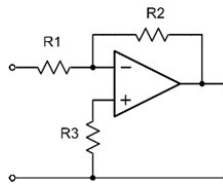
- (a) $(R1 / R2)$

Questions

- (b) $-(R2 / R1)$
- (c) $R1 - R2 + R3$.

9. The circuit shown is:

- (a) an inverting amplifier
- (b) a non-inverting amplifier
- (c) a differential amplifier.



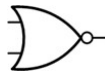
rq3

10. The symbol shows a:

- (a) two-input OR gate
- (b) two-input AND gate
- (c) two input NOR gate.

11. In order to produce a logic 1 output from Y:

- (a) both input A and input B must be at logic 0
- (b) both input A and input B must be at logic 1
- (c) both input A and input B must have the same logic state (either 0 or 1).



rq4



rq5

12. An unused input on a CMOS logic gate must be:

- (a) left disconnected
- (b) allowed to 'float', either high or low
- (c) tied to logic 1 or logic 0.

13. The small circle shown at the output of a logic gate symbol indicates:

- (a) inversion
- (b) the OR function
- (c) the AND function.

14. For CMOS logic a logic 1 state is represented by a voltage that is:

- (a) equal to the positive supply voltage
- (b) greater than 50% of the positive supply voltage
- (c) greater than 70% of the positive supply voltage.

15. A voltage of +3.5 V appears at the input of a CMOS logic gate operating from a +6 V supply. The corresponding logic level is:

- (a) logic 0
- (b) logic 1
- (c) indeterminate.

Answers are provided on page 39

About this course

Introduction

This workbook is intended to reinforce the learning that takes place in the classroom or lecture room. It provides a series of practical activities and investigations that complement syllabus section 4.1.3 of EASA Part-66 Module 4, Electronic Fundamentals. Locktronics equipment makes it simple and quick to construct and investigate electrical circuits. The end result can look exactly like the circuit diagram, thanks to the symbols printed on each component carrier.

Aim

The workbook aims to introduce students to the basic underpinning principles and concepts of aircraft electrical and electronic equipment. It also provides a useful introduction to electrical measurements and the use of ammeters, voltmeters and oscilloscopes.

Prior Knowledge

Students should have previously studied (or should be concurrently studying) EASA Module 3 (Electrical Fundamentals) or should have equivalent knowledge at Level 3.

Learning Objectives

On successful completion of this course the student will have learned to:

- recall the basic properties and characteristics of operational amplifiers;
- describe the meaning and significance of output saturation;
- explain the significance of the term 'high gain differential voltage amplifier';
- distinguish between the performance of a comparator and a Schmitt trigger circuit;
- draw the circuit diagram for a sensing unit connected to a comparator;
- draw the circuit diagram for a sensing unit connected to a Schmitt trigger;
- analyse the behaviour of an inverting Schmitt trigger;
- identify the op-amp non-inverting amplifier circuit;
- recall and use the formula for the voltage gain of an op-amp non-inverting amplifier;
- measure the voltage gain of op-amp voltage amplifiers;
- describe and explain the use of op-amp voltage followers;
- identify the op-amp summing amplifier circuit;
- recall and use the formula for the voltage gain of an op-amp summing amplifier;
- identify the op-amp difference amplifier circuit;
- calculate the output voltage of a given op-amp difference amplifier;
- identify the op-amp differentiator circuit;
- recall the significance of time constant to the performance of the differentiator circuit;
- sketch of output waveform expected from the differentiator for a given input waveform;
- identify the op-amp integrator circuit;
- sketch of output waveform expected from the integrator for a given input waveform;
- recall the basic properties and characteristics of AND, OR and NOT logic gates;
- identify logic levels in relation to the supply voltages for CMOS logic circuits;
- explain the logical operation of NOT, AND, and OR logic gates.
- Fibre optic transmitter receiver circuits

What students will need:

This pack is designed to work with the Locktronics Aircraft Maintenance Kit. The electrical / electronic parts required for this workbook are listed on the next page. Students will also need:

- either two multimeters, such as the LK1110, capable of measuring currents in the range 0 to 200mA, and voltages in the range 0 to 200V;
- or equivalent ammeters and voltmeters.

For other modules in the series, they will need:

- a function generator, such as the LK8990, or equivalent;
- and an oscilloscope capable of monitoring the signals it produces.

If you are missing any components, or need additional items, please contact Matrix or your local dealer.

Power sources:

Students will need to make use of an adjustable low-voltage DC supply. The output voltage from the supplied DC power unit can be adjusted to provide outputs of either 3 V, 4.5 V, 6 V, 7.5 V, 9 V or 13.5 V, with currents typically up to 1 A. The voltage is changed by turning the selector dial just above the earth pin until the arrow points to the required voltage.

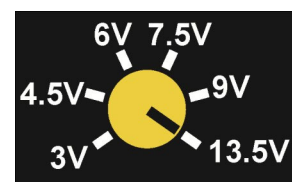
Tutors may decide to make any adjustment necessary to the power supply voltage, or may allow students to make those changes.

Each exercise includes a recommended voltage for that particular circuit.

In the example opposite, the DC power supply has been adjusted to provide an output of 13.5 V DC.



p28a



p28b

The table below shows the parts needed for all 4 workbooks in the Electronic fundamentals series.

Qty	Code	Description			Qty	Code	Description
2	HP 2666	12V adjustable DC power supply			4	LK5603	Lead, red, 500mm, 4mm to 4mm stackable
1	HP 3728	AC power supply, 12VAC, 15A, UK			4	LK5604	Lead, black, 500mm, 4mm to 4mm stackable
1	LK2340	AC voltage source carrier			4	LK5607	Lead, yellow, 500mm, 4mm to 4mm stackable
1	LK3548	Fibre optic Transmitter			4	LK5609	Lead, blue, 500mm, 4mm to 4mm stackable
1	LK3982	Voltmeter, 0V to 15V			1	LK6202	Capacitor, 100uF, Electrolytic, 25V
1	LK4002	Resistor, 100 ohm, 1W, 5% (DIN)			1	LK6205	Capacitor, 1uF, Polyester
1	LK4003	Capacitor, 1000 uF, Electrolytic 30V			3	LK6206	Capacitor, 4.7uF, electrolytic, 25V
1	LK4123	Transformer, 2:1 turns ratio			2	LK6207	Switch, push to make, metal strip
1	LK4663	Low power solar motor			1	LK6209	Switch, on/off, metal strip
3	LK5202	Resistor, 1k, 1/4W, 5% (DIN)			1	LK6214	Capacitor, VARIABLE, 0-200pF
3	LK5203	Resistor, 10k, 1/4W, 5% (DIN)			3	LK6216	Capacitor, 0.47 uF, Polyester
1	LK5205	Resistor, 270 ohm, 1/2W, 5% (DIN)			1	LK6218	Resistor, 2.2k, 1/4W, 5% (DIN)
2	LK5207	Resistor, 180 ohm, 1/2W, 5% (DIN)			1	LK6224	Switch, changeover, toggle
1	LK5208	Potentiometer, 250 ohm (DIN)			1	LK6224	Changeover switch
1	LK5209	Resistor, 5K6 ohm, 1/2W, 5% (DIN)			1	LK6232	Resistor, 500k, 1/4W, 5% (DIN)
2	LK5214	Potentiometer, 10k (DIN)			1	LK6234L	Op Amp Carrier (TL081) with 2mm to 4mm Leads
2	LK5218	Resistor, 100k, 1/4W, 5% (DIN)			1	LK6238	Resistor, 200k, 1/4W, 5% (DIN)
2	LK5224	Capacitor, 47uF, Electrolytic, 25V			1	LK6239	Capacitor, 1nF, Polyester
2	LK5240	Transistor RHF, NPN			2	LK6635	LED, red, 5V (SB)
1	LK5241	Transistor LHF, NPN			1	LK6706	Motor 3 to 12V DC, 0.7A
1	LK5242	Diode, germanium			1	LK6774	Fibre optic cable - 1m
4	LK5243	Diode, power, 1A, 50V			1	LK6860	AND gate carrier (ANSI)
1	LK5247	Zener diode, 4.7V			1	LK6861	OR gate carrier (ANSI)
1	LK5248	Thyristor			2	LK6862	NOT gate carrier (ANSI)
24	LK5250	Connecting Link			1	LK7409	AA battery holder carrier
1	LK5254	Zener diode, 8.2V			1	LK7483	1:1 transformer with retractable ferrite core
1	LK5255	Transistor RHF, PNP			2	LK8275	Power supply carrier with battery symbol
1	LK5256	Transistor LHF, PNP			1	LK8275	Fibre optic receiver
1	LK5266	Bridge rectifier			1	LK8492	Dual rail power supply carrier
1	LK5402	Thermistor, 4.7k, NTC (DIN)			2	LK8900	7 x 5 metric baseboard with 4mm pillars
					2	LK9381	Ammeter, 0mA to 100mA

Using this course:

It is expected that the worksheets are printed / photocopied, preferably in colour, for the students' use. Students should retain their own copy of the entire workbook.

Worksheets usually contain:

- an introduction to the topic under investigation and its aircraft application;
- step-by-step instructions for the practical investigation that follows;
- a section headed 'So What?' which aims both to challenge learners by questioning their understanding of a topic and also provides a useful summary of what has been learned. It can be used to develop ideas and as a trigger for class discussion.
- a section headed 'Questions' which provides further work for students to carry out. Answers to these questions are provided at the end of this workbook.

This format encourages self-study, with students working at a rate that suits their ability. It is for the tutor to monitor that students' understanding is keeping pace with their progress through the worksheets and to provide additional work that will challenge brighter learners. One way to do this is to 'sign off' each worksheet, as a student completes it, and in the process have a brief chat with each learner to assess their grasp of the ideas involved in the exercises that it contains.

Finally, a set of examination 'Revision Questions' has been provided to conclude the work on each topic. These questions are of mixed difficulty and are typical of those that students will face when they sit their Module 4 CAA examinations. It is recommended that students should attempt these questions under examination conditions and without the use of notes or calculators.

Time:

It will take most students between eight and ten hours to complete the full set of worksheets. It is expected that a similar length of time will be needed to support the learning in a class, tutorial or self-study environment.

Worksheet	Notes for the Tutor	Timing
1	<p>The first issue is to familiarise students with the pinout of the op-amp, and to explain the significance of the 'inverting' and 'non-inverting inputs. At this stage, no attempt is made to introduce the offset null connections.</p> <p>The op-amp carrier uses a LM10 op-amp, which is based on the industry-standard '741' but with vastly improved characteristics, especially input impedance. The students will meet this concept later in the course. For now, they may need to have the idea of a dual-rail power supply explained to them. The physical reality is that there is no such thing as 0V in this circuit. Although the power rails are labelled +6V / 0V / -6V, that is simply to conform to convention. They could equally well be labelled 12V / 6V / 0V. However, the convention is that voltages are measured from the centre voltage, and this is called 0V.</p> <p>The aim of the first part of the investigation is merely to show that the output switches rapidly from one extreme (saturation voltage) to the other as the input voltage changes relative to the reference voltage set by the two equal resistors. The second stage measures the input voltages to investigate more closely this changeover. Students should be able to use a digital multimeter to measure voltage, though the instructor may have to remind them how to do this. Finally, the student swaps over the inputs to see the effect.</p> <p>The 'So what?' section explains the significance of the description 'high gain differential voltage amplifier' and gives the formulae for voltage gain and for the basic behaviour of the op-amp. At this stage, there is no mention of feedback. The role of this circuit as a voltage comparator is described, but this may need to be driven home through a number of examples.</p>	30 - 45 minutes
2	<p>In Worksheet 1, students met the comparator. In this worksheet, they attach a temperature-sensing unit to one of the inputs, and a variable reference voltage, provided by a 'pot', to the other.</p> <p>Although students should know the difference between a variable resistor and a potentiometer, they may need the instructor's help to set up the 'pot'. In particular, the instructor should check that the 10kΩ resistor, and not the 'shorted' output, is connected between the power supply rails. A simple rule is that resistors have two 'legs' and so do variable resistors. The 'pot' uses all three legs. The secret of success is to adjust the 'pot' so that the LED is about to turn off. The slightest change to the temperature of the thermistor should then make that change happen.</p> <p>The investigation then turns to the Schmitt trigger circuit. The aim is that students realise that the single switching threshold of the comparator can cause problems when the output of the sensor is subject to high levels of electrical noise, or any other factor that causes the output voltage to 'wobble'. When near the switching threshold, this variation may be enough to make the output switch rapidly from one saturation value to the other. This 'hunting' can have serious consequences for the device attached to the output of the comparator, or to the comparator itself, as current demand rises sharply when switching takes place.</p>	30 - 45 minutes

Worksheet	Notes for the Tutor	Timing
2	<p>continued...</p> <p>The Schmitt trigger overcomes this problem by having two switching thresholds. The output switches from negative to positive saturation at a low voltage, but stays there even if the voltage rises slightly (i.e. no hunting.) The output changes back only if the input rises to a relatively high voltage, (but then stays there even if the input fluctuates.) The circuit studied is known as an inverting Schmitt trigger. There is a non-inverting Schmitt trigger, but its analysis is a bit more complicated. Able students could be given the task of researching that circuit.</p>	
3	<p>Now the students meet feedback. The instructor might wish to expand on the ideas of positive and negative feedback, as both are used in this module. Negative feedback always produces a calming effect on the circuit. It makes the output less likely to saturate. It reduces the huge open-loop voltage gain of the op-amp to a more manageable level. The idea of an amplifier is that the output follows the input, but is a larger version of it. If the output saturates, it can no longer follow changes in the input. Amplifiers use negative feedback, as their outputs should never saturate. Positive feedback, on the other hand, drives the output into saturation more readily, making it unlikely that the output is ever out of saturation. It is used in oscillators and Schmitt triggers, where the output is required to be in one value of saturation all the time.</p> <p>While amplifiers are usually associated with audio systems, it makes sense to begin the investigation by using DC signals. These are easier to visualise and, probably, to measure. As students will discover in worksheet 5, these amplifiers have the same behaviour for DC and for low frequency AC signals.</p> <p>The voltage gain of the amplifier is determined solely by the value of the two resistors, R_F and R_1, provided extreme values of gain or bandwidth are avoided. This investigation looks at two pairs of resistor values, to give gains of 2x and 11x. The instructor may wish to add other values, or vary the values between different groups and then later collate results.</p> <p>Students often confuse the voltage gain formula ($= V_{OUT} / V_{IN}$) and the voltage gain formula showing the dependence on resistor values ($= 1 + R_F/R_1$.) Instructors should provide a range of examples to reinforce the significance of these formulae.</p> <p>The analysis in 'So what?' introduces the ideal characteristics of op-amps. These will need a deal of reinforcement by the instructor, as some are fairly esoteric concepts. The important idea in there is the input impedance. As we are dealing with DC signals, this can be called input resistance here. The significance is that many signal sources can generate a reasonable voltage, but are unable to deliver appreciable current. If the amplifier draws much current from these sources, the voltage transferred to the amplifier will be very small. Most of the signal voltage will be dropped across the output (but internal) resistance of the signal source. The big advantage of the non-inverting amplifier over the inverting amplifier is that the former has a much higher input impedance, and so draws a much smaller current from the signal source.</p>	30 - 40 minutes

Worksheet	Notes for the Tutor	Timing
4	<p>The first part of the investigation demonstrates the piece of wire effect - $V_{OUT} = V_{IN}$. The second part shows the more subtle effect. This can be done in other ways, depending on the equipment available to the students. Here it is shown that when the temperature-sensing unit is connected directly to the fan motor, the latter has such a low impedance (resistance) that the voltage signal from the sensing unit collapses, and the motor does not turn. Using the voltage follower to interface the motor and sensing unit rectifies this. The current delivered to the motor is drawn from the power supply to the op-amp. This current is controlled by the signal from the temperature-sensing unit. Students may need to dwell for a while on this concept, and the instructor should be ready to explain what is going on.</p> <p>The 'So what?' section goes into detail about voltage transfer between subsystems, but students may need help in understanding this idea. Instructors should point out that when the signal is passed to the output transducer, loudspeaker for example, then power transfer is probably more important, i.e. the requirement is to transfer not only a high voltage but also a large current. That changes the rules radically!</p> <p>Another area where reinforcement may be needed is that of 100% negative feedback. The initial reaction of the student may be that if the full output signal is subtracted from the input signal, then nothing is left!</p>	45 - 60 minutes
5	<p>This investigation mirrors that in Worksheet 3, but uses an inverting amplifier. The formula for voltage gain is applied to the results. The formula linking voltage gain to resistor values is given without proof, but will need additional examples to cement it into the students' minds.</p> <p>The 'So what?' section includes an important practical detail, that for any op-amp circuit where the output is not saturated, the two inputs sit at virtually the same input. Some students might puzzle at the role of the op-amp in the two voltage amplifier circuits. The voltage gain formulae make no mention of it! The answer is that the op-amp is trying its hardest to keep the two inputs at the same voltage. If the output saturates, then it has failed.</p> <p>Here is a very practical means of checking that the op-amp is functioning properly. Provided the output is not saturated, a DMM connected to first one and then the other input should give the same reading.</p> <p>The point is also made that the input resistor, R_{IN}, should be as large as is practicable in order to keep a high input resistance for the amplifier (which really is equal to the value of the input resistor.)</p>	35 - 45 minutes

Worksheet	Notes for the Tutor	Timing
6	<p>Once again, the title describes what this subsystem does. However, it does so only if equal-sized resistors are used throughout! Students should find that the early part of Part 1, the summing amplifier, works as expected, but that the second part, where the value of the feedback resistor is reduced to $1k\Omega$, produces a more thought-provoking outcome. In practice, this is an amplifier, and so we need to avoid output saturation. The output sums the input signals, and may add a weighting factor. As a result, it is easy to cause saturation. To avoid it, keep the voltage gain to a small value by reducing the size of the feedback resistor.</p> <p>Students are asked to deduce a relationship between output and input voltages and then to test their ideas by predicting the output for a new set of conditions. Equally, the instructor could give them the input voltages and ask them to determine the resulting output.</p> <p>The 'So what?' section introduces a significant result for this circuit in the form of the relationship for the output voltage in terms of the two input voltages and the resistance values used. Instructors may wish to consider the effect on the output voltage of each input independently and then combine the results in order to derive a single equation for the output voltage. Instructors may also wish to show how further inputs can easily be added to the circuit.</p>	45 - 60 minutes
7	<p>The difference amplifier is similar to the summing amplifier, but different! The function is suggested by the name. However, its major application is as an instrumentation amplifier. These have to amplify the significant section of the signal presented to them by sensors, while rejecting unwanted components caused by electrical noise, or temperature variations etc.</p> <p>Students are asked to notice the symmetry of the circuit diagram. This may help them to remember how to draw it. The instructor may wish to emphasise this feature to the students. The instructions suggest suitable values for the input voltages, but the instructor may wish to vary these, or allocate different values to different groups. As usual, the danger is that the output saturates, and the instructor should take care to avoid this when selecting voltage or resistor values.</p> <p>Students are once again asked to deduce a relationship between output and input voltages and then to test their ideas by predicting the output for a new set of conditions. Equally, the instructor could give them the input voltages and ask them to determine the resulting output.</p> <p>The 'So what?' section analyses the behaviour of the circuit, assuming that no current flows into the op-amp inputs i.e. assuming that the op-amp is ideal and so has infinite input impedance. This analysis is not easy, and the instructor should spend time going through it with the students, and getting them to work on similar arrangements that use different voltages and/or resistor values.</p>	45 - 60 minutes

Worksheet	Notes for the Tutor	Timing
8	<p>In this worksheet students will investigate a differentiator based on an operational amplifier. They will do this by applying a square wave to the input of the differentiator circuit and observing the resulting output waveform. Since students may not have met differentiating circuits before, they will benefit from an explanation of why a square wave makes an appropriate waveform for testing this circuit. It should be explained that the steep rising and falling edges of a square wave exhibit a very rapid rate of change whilst the 'flat' positive and negative edges exhibit zero rate of change of voltage with time. You should also point out that the operational amplifier is used in an inverting configuration—hence they should expect the output to be inverted and have negative polarity for a positive going input, and vice versa. The aim of this explanation should be to provide students with sufficient information to be able to justify the shape of the output waveform when they compare it with the input.</p> <p>Students should set up the differentiator circuit, making use of two DC power supplies to produce the symmetrical +/-6V power supply rails. The input of the differentiator should be connected to a function generator (ideally with an output impedance of 50 Ω, or less) adjusted to produce a square wave output of 1V pk-pk at a frequency of 100 Hz.</p> <p>Students will once again need a dual-channel oscilloscope (or equivalent virtual instrument, such as Picoscope) with which to display the input and output waveforms. Where necessary, Instruction on using this test instrument should be given before students begin their own measurements. It is also important to remind students that the common ground connection to the oscilloscope should be taken to the 0V rail.</p> <p>Students should make the necessary adjustments to display at least two cycles of the input and output waveforms using a common time scale. They should then sketch the waveforms that they have observed, making sure to include labelled axes of voltage and time. Alternatively, where a virtual instrument is used, it should be possible to capture the screen data and transfer this as an image file to hard copy.</p> <p>With students that have a grounding in calculus, it might be useful to introduce and explain the significance of the expression for the output voltage of the differentiator. More able students should be encouraged to understand the operation of the circuit in relation to the time constant, CR, of the circuit (470 μs) and the periodic time of the input square wave (10 ms).</p>	45 - 60 minutes

Worksheet	Notes for the Tutor	Timing
9	<p>This worksheet is similar to the last worksheet but this time students will investigate an integrator based on an operational amplifier. Once again, they will do this by applying a square wave to the input of the differentiator circuit and observing the resulting output waveform. Since students may not have met integrating circuits before, they will benefit from an explanation of why a square wave makes an appropriate waveform for testing this circuit. It should be explained that the area enclosed by the positive and negative half-cycles increases in a linear fashion with time. Once again, you should also point out that the operational amplifier is used in an inverting configuration—hence students should expect the output to be inverted and have negative polarity for a positive going input, and vice versa. The aim of this explanation should be to provide students with sufficient information to be able to justify the shape of the output waveform when they compare it with the input.</p> <p>As before, students should set up the integrator, making use of two DC power supplies to produce the symmetrical $\pm 6V$ power supply rails. The input of the differentiator should be connected to a function generator (ideally with an output impedance of 50Ω, or less) adjusted to produce a square wave output of $1V$ pk-pk at a frequency of 100 Hz.</p> <p>Students will again need a dual-channel oscilloscope (or equivalent virtual instrument, such as Picoscope) with which to display the input and output waveforms. Where necessary, Instruction on using this test instrument should be given before students begin their own measurements. It is also important to remind students that the common ground connection to the oscilloscope should be taken to the $0V$ rail.</p> <p>Students should make the necessary adjustments to display at least two cycles of the input and output waveforms using a common time scale. They should then sketch the waveforms that they have observed, making sure to include labelled axes of voltage and time. Alternatively, where a virtual instrument is used, it should be possible to capture the screen data and transfer this as an image file to hard copy.</p> <p>With students that have a grounding in calculus, it might be useful to introduce and explain the significance of the expression for the output voltage of the integrator. Once again, more able students should be encouraged to understand the operation of the circuit in relation to the time constant, CR, of the circuit ($470 \mu s$) and the periodic time of the input square wave (10 ms).</p>	45 - 60 minutes

Worksheet	Notes for the Tutor	Timing
10	<p>This worksheet introduces the first, and simplest, logic gate, the NOT gate. Before that, the introduction makes the necessary distinction between logic gates and logic functions. The more important is the logic function. There are a number of ways to implement a logic function. In digital electronics, you can use a dedicated, discrete logic gate, you could use a series of NAND gates, or NOR gates, or use a programmable system. On a wider front, optical logic gates produce the same logic functions, but using laser light, to speed up the switching process. The technology may differ, but all produce the same out- comes in terms of logic functions. The introduction also contains an important table of logic symbols, both in the ANSI format, and the BS (sometimes called SB) format. The students may encounter further formats, such as the IEC (International Electrotechnical Commission) system. The investigation involves setting up a switch unit and using it to generate a digital input signal for a NOT gate. The students use this to construct a voltage truth-table for the NOT gate. They then invert the switch unit, but observe that this has no effect on the NOT function itself.</p> <p>The 'So What' section details the voltage bands used by CMOS gates (like that used on the Locktronics NOT gate carrier), and the students use this information to turn their voltage measurements into logic levels, and re-build the truth-table. The students then investigate what happens when the resistor is removed from the switch unit. In general, this is an unwise move for CMOS gates. The inputs operate on minute currents and so can be affected by stray electromagnetic fields, such as radio, radar and navigation aids. As a result, the inputs can switch rapidly between logic 0 and 1. As they do so, they draw enough current to cause local overheating, which can damage the IC. The rule, then, is that CMOS inputs should not be allowed to 'float', but instead must be either 'pulled down' to the 0V rail, or 'pulled-up' to the positive power rail, by a resistor. The Locktronics NOT carrier has unconnected inputs connected internally to 0V by a large value resistor.</p> <p>Finally, as a foretaste of what is to come, the students check the serial number of the chip used in the NOT carrier. CMOS NOT gates carry the serial number 4049. However, the one used on the carrier is a 4011— a NAND gate. This highlights the fact that that it is often more appropriate to generate logic functions using other logic gates, especially NAND gates.</p>	45 - 60 minutes

Worksheet	Notes for the Tutor	Timing
11	<p>This worksheet investigates the behaviour of an AND gate. It introduces a situation in which the AND function would be encountered in an aircraft. Instructors may wish to use further examples to illustrate the importance of logic in an aircraft.</p> <p>The diagram on page 23 includes a pull-down resistor, to ensure that output sits at logic 0 when either switch is open. Again, the significance of this needs to be emphasised. The students set up two switch units and use them to input four combinations of logic signals. Measuring input and output voltages, they complete a table of results, which they then turn into logic levels, and generate the AND gate truth-table. They are encouraged to view the AND function as one which generates a logic 1 output only when both inputs are at logic 1.</p> <p>A similar approach is now used to investigate the OR gate. The introduction points out a way to view the OR function as two switches in parallel. Again, the diagram includes a pull-down resistor, to ensure that output sits at logic 0 when both switches are open. The significance of both points needs to be emphasised by the instructor.</p> <p>As before, the discussion in the 'So What' section leads to the building of the truth- table for the OR gate.</p> <p>The 'So What' section also shows the pin connecting diagrams for CMOS 4081 (quad two-input AND) and 4071 (quad two-input OR) integrated circuits. Part of the importance is to highlight again the need to avoid floating inputs. Zealous students often take this message too far, and connect unused outputs to the nearest power rail. This is unfortunate, because the nature of the logic function applied by the gate may try to drive the output to logic 1, while the student has connected it to the 0V rail, or vice-versa. The message then is that the outputs take care of themselves. It is only unused inputs that require our attention.</p> <p>Finally, students should be reminded that they will study a large number of other digital logic devices and combinational logic systems (e.g. coders and decoders) when they progress to Module 5.</p>	45 - 60 minutes
12	<p>This is a very simple worksheet - students just need to understand how fibre optics work and understand that one possible reason for failure is that connections are not made properly.</p>	10 minutes

Revision question paper

1. (b)
2. (c)
3. (b)
4. (a)
5. (c)
6. (b)
7. (a)
8. (b)
9. (a)
10. (c)
11. (a)
12. (c)
13. (a)
14. (c)
15. ©

31 07 23 Reformatted to new style

Version control



06 01 22 Fibre optic transmitter and receiver added to kit and worksheets.
18 09 23 page 8 - values in tables changed
Page 30 - BOM change