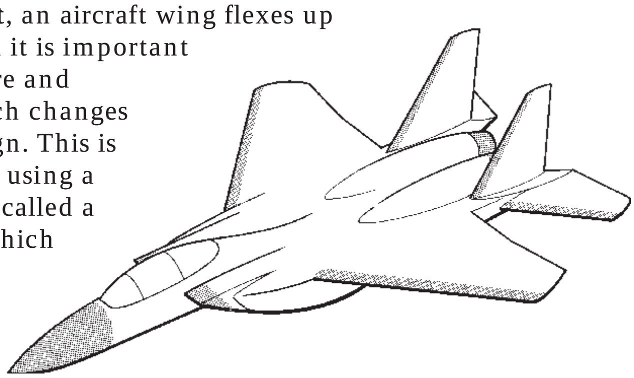
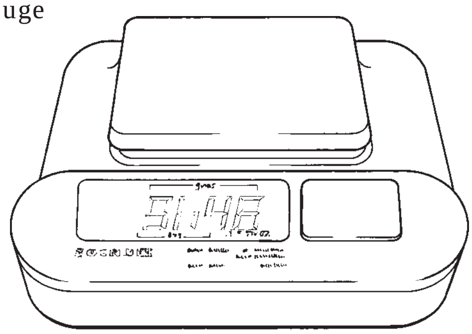
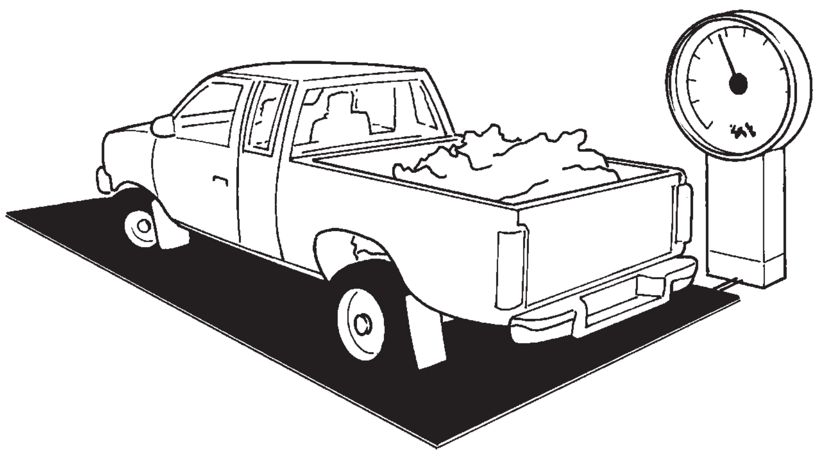
SIGNALS FROM STRAIN: DESIGNING AND MAKING 'OVERLOAD PROTECTION' SYSTEMS

When a material or structure is stressed, dimensional changes take place. In the case of an aircraft wing, for example, these dimensional changes are complex and sometimes very small. In flight, an aircraft wing flexes up and down, and it is important to plot, measure and understand such changes during its design. This is normally done using a form of sensor called a *strain gauge* - which changes its resistance when strained.

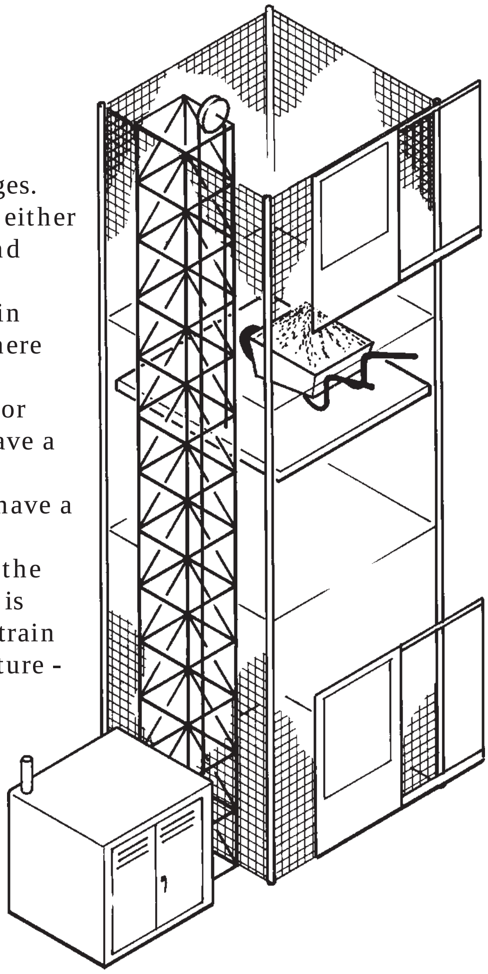


A similar sensing principle is used in weighing machines to give an electronic digital readout. A strain gauge is attached to a spring which undergoes a dimensional change in proportion to the load applied to it. The change in resistance of the strain gauge is then converted into an electrical signal to be displayed in some way. A combination of spring and strain gauge is known as a *load cell* and is found in both small domestic weighing machines and larger weight bridges for vehicles.





DESIGN OPPORTUNITIES

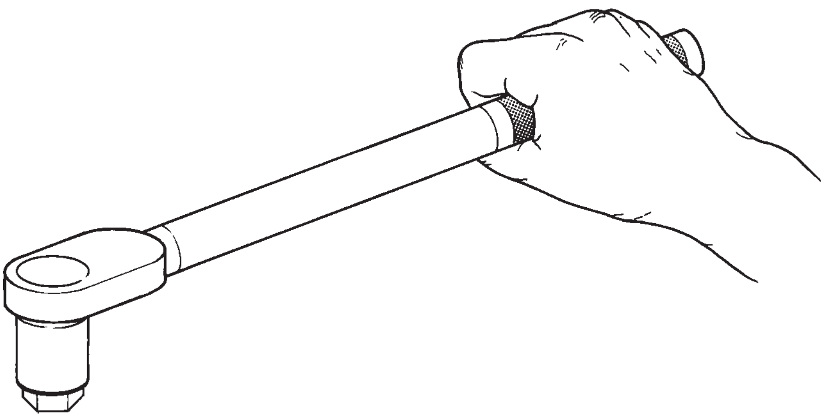


There are many and varied applications for strain gauges. Apart from applications in either weighing or monitoring and data logging, they are used increasingly, for example, in safety (control) systems where overload protection is important. Building sites, for example, use lifts which have a maximum safe working capacity. An ideal lift will have a failsafe "mechanism" that sounds an alarm, prevents the lift working - or both - if it is overloaded. One or more strain gauges placed on the structure - and sensing minute dimensional changes - can be used as part of an electronic system signalling overload conditions.

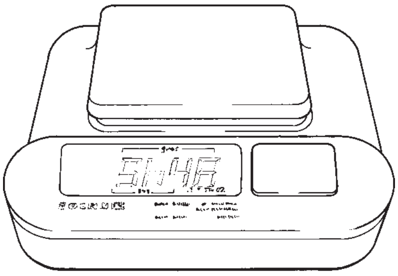
There are likely to be many local contexts where some form of 'overload' indication is needed and where a strain gauge and appropriate circuit can be employed. Examples include the following:

- Overload protection for a fork lift truck (and other small vehicles).

- A simple yes/no indicator for torque applied to nuts or bolts - a form of torque wrench.



- A weighing machine that indicates preset quantities or units.



DESIGN SPECIFICATION

When a brief has been agreed on, it is necessary to draw up a design specification. This is a detailed description of what a system would be like, what it will do and who will use it. Any 'overload' system based on a strain gauge will require three main 'building blocks':

- Strain gauges to 'sense' dimensional change
- A Wheatstone bridge to provide an output signal (voltage)
- Operational amplifiers to operate as instrumentation amplifier and possibly a comparator

The following notes provide guidance on these building blocks and on adding them together.

STRAIN GAUGES

Strain gauges are used to measure strain. Strain is a measure of how much a material has changed in length. This could be either the shortening of the material due to compressive forces or the lengthening of the material due to tensile forces. It is always expressed in the form of a ratio. This allows dissimilar materials of varying cross-sections to be compared. A figure for strain is calculated by using the formula;

$$\text{Strain (e)} = \frac{\text{Change in length (dl)}}{\text{Original length (L)}}$$

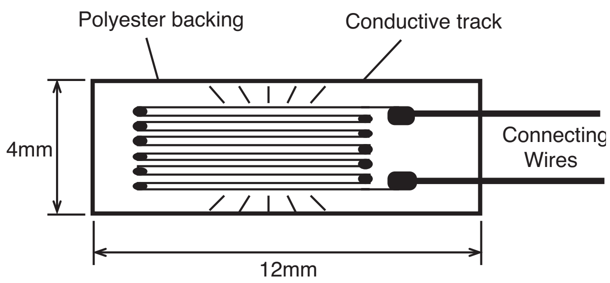
Under normal conditions most constructional materials do not perceptibly move when a normal working load is applied to them, but minute changes in length do take place. It is possible to sense these changes in length using a strain gauge.

Strain gauges work on the principle that the electrical resistance of a conductor changes as it is stretched, so becoming longer and thinner. In fact the resistance of a conductor is proportional to its length and inversely proportional to cross-sectional area. So mathematically,

$$\text{Resistance} \propto \frac{\text{Length}}{\text{Area}}$$

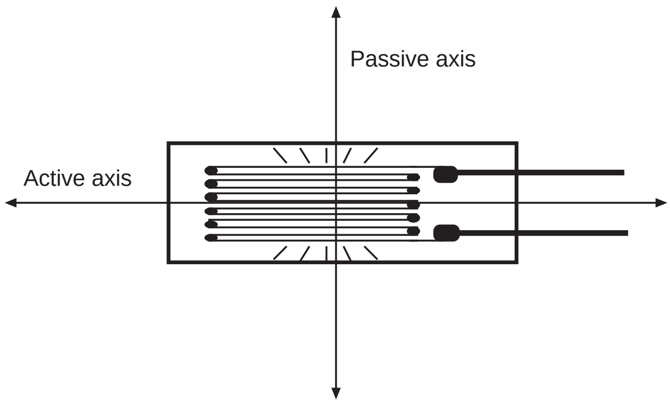
Increasing the length, or reducing the area, will increase the resistance.

Because the changes in length of a material are normally very small, the change in resistance of a single conductor would also be very small. To overcome this problem strain gauges have a single conductor that is arranged into very compact rows. This means that a long conductor is packed into a small area. The conductor is formed by etching the pattern into a thin metal foil that is bonded to a polyester backing. They are produced in a very similar way to a photo-etched PCB.



A strain gauge

The pattern of the conductor means that the strain gauge will have an **active axis** and a **passive axis**. The active axis is in line with the rows of conductors and this should be fixed along the direction that you want to measure the strain. The passive axis is at 90° to the rows of conductors. Any movement on the passive axis will have very little effect on the gauge.



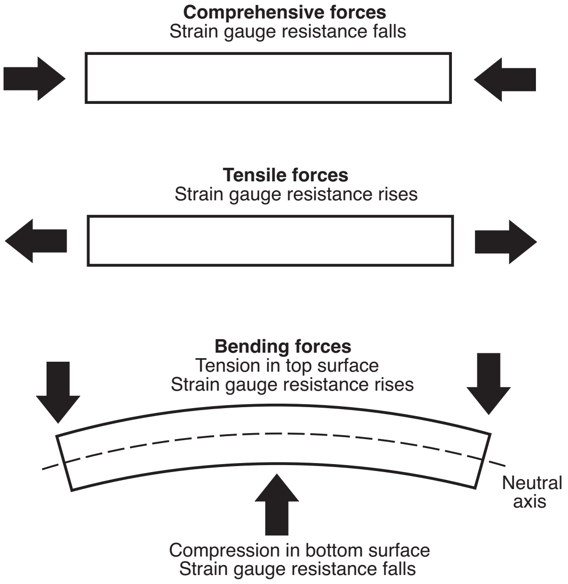
All of the circuits in this unit are based upon a strain gauge available from R.S. components (part number 308-118). Its resistance is nominally 120Ω.

The gauge needs to be securely fixed to the material that is to be measured using a strong adhesive.

When compressive forces are applied to the material then the strain gauge will compress and its resistance will fall. When tensile forces are applied to the material the strain gauge will stretch and its resistance will rise.

Strain gauges can also be used to sense when a material is bending. When a piece of material bends the material on either side of the **neutral axis** will either compress or stretch.

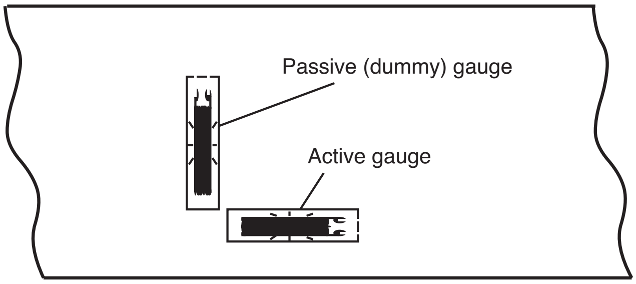
It is the change in resistance of the strain gauge that is used to give an indication of strain.



To further improve the accuracy of this sensing concept it should be noted that temperature will also have an effect on the resistance of a metal conductor. As the temperature rises the resistance will fall. To overcome this problem strain gauges are often used in pairs.

The two strain gauges are mounted at 90° to each other.

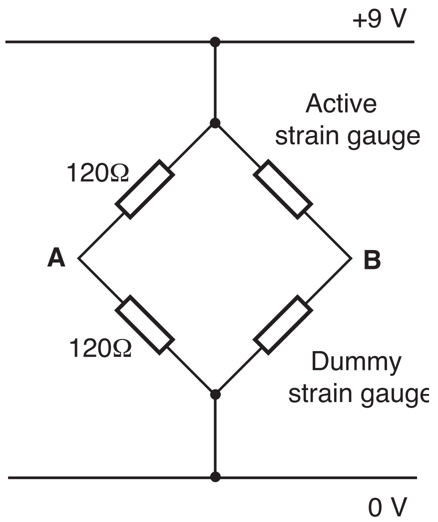
One is an active gauge as its active axis is in line with the applied force. This one measures the strain. The other is a passive, or 'dummy', gauge as its passive axis is in line with the applied force. Both gauges will change their resistance by the same amount due to temperature changes. This balances out the unwanted temperature effect.



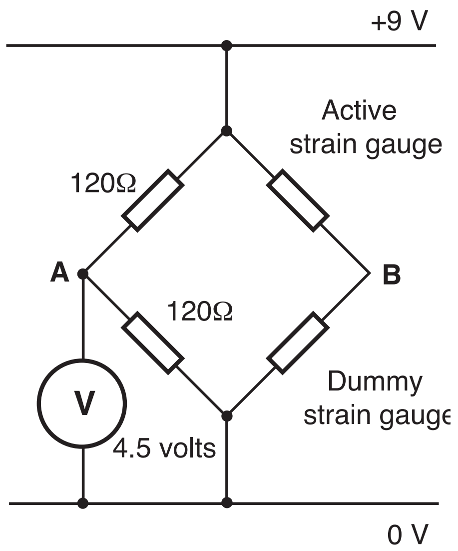
Further electronic circuitry is needed to convert this small change in resistance into a usable signal. The first step is to incorporate the two strain gauges into a circuit known as the 'Wheatstone bridge'.

THE WHEATSTONE BRIDGE

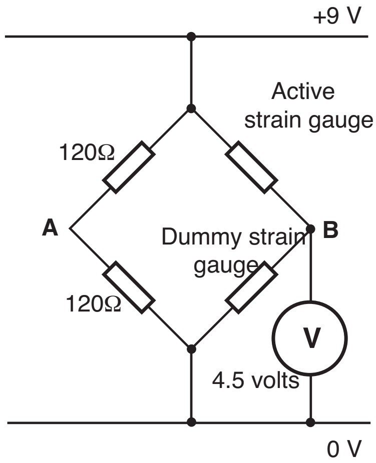
This is a potential divider network that contains four resistors. The four resistors are arranged in a diamond between power supply rails. Two of the resistors are fixed and the other two are the active and passive strain gauges. The signal is taken from the two junction points.



If the two fixed resistors are equal then the voltage at point **A** with respect to zero will be half of the supply voltage, i.e. 4.5 volts.



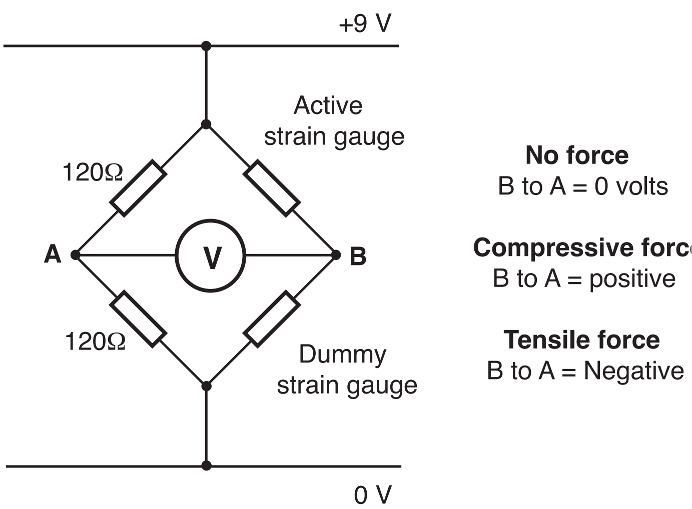
If there is no force applied to the material then both strain gauges will have an equal resistance. The voltage at point **B** with respect to zero will again be half of the supply voltage, i.e. 4.5 volts.



If the temperature rises or fall then the resistance of the strain gauges will change. However, both strain gauges will change by the same amount so the voltage at point **B** with respect to zero will remain at 4.5 volts. This ability to compensate for the effects of resistance change due to temperature is the primary reason for using a Wheatstone Bridge.

The output voltage, or signal, is taken from point **B** with respect to point **A**. So in this resting condition the output voltage would be 0 Volts as there is no potential difference between the two points.

If the material is loaded with a compressive force the active strain gauge will compress and its resistance will reduce. This will cause the voltage at point **B** to rise. The output signal will, therefore, rise positively. The greater the amount of compressive force that is applied to the material the more positive the output signal becomes. If the compressive load is removed from the material then the output signal will fall to zero again.



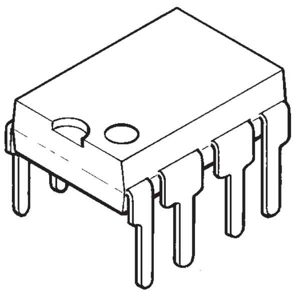
If the material is loaded with a tensile force the active strain gauge will stretch and its resistance will rise. This will cause the voltage at point **B** to fall. The output signal will, therefore, fall negatively. The greater the amount of tensile force that is applied to the material the more negative the output signal becomes. If the tensile load is removed from the material then the output signal will rise to zero again.

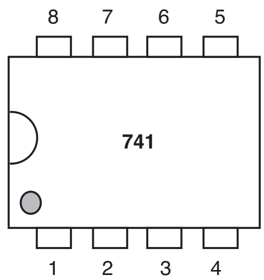
The Wheatstone Bridge converts the change in resistance of the strain gauge to a change in voltage. The voltage rises positively from 0 volts as compression increases and falls negatively from 0 Volts as tension increases.

The change in resistance is small, so the change in voltage, or output signal, will also be small. If this is to be of use in providing an indication of strain then it must be amplified. A very good type of amplifier circuit to use for this application comes in the form of an I.C. and is known as an operational amplifier.

OPERATIONAL AMPLIFIERS (OP AMPS)

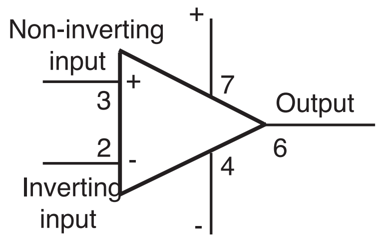
There are a number of different types of Op Amp. Perhaps the most common, and the one that we will use here, is the 741. These are relatively cheap and readily available. They come in an eight pin DIL package.





The I.C. contains some 20 transistors, 11 resistors and one capacitor. The advantages of using an Op Amp for this application is that they can amplify both positive and negative inputs and they have a predictable gain that can be set by external components.

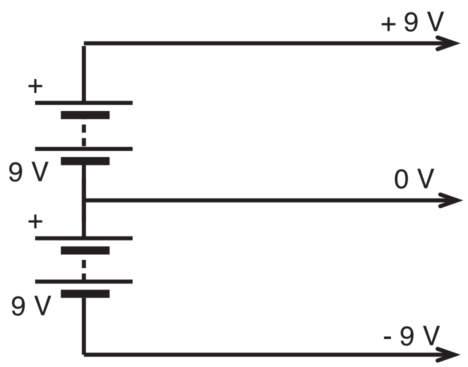
The circuit symbol for an Op Amp is shown here. Notice that it has two separate inputs and one output.



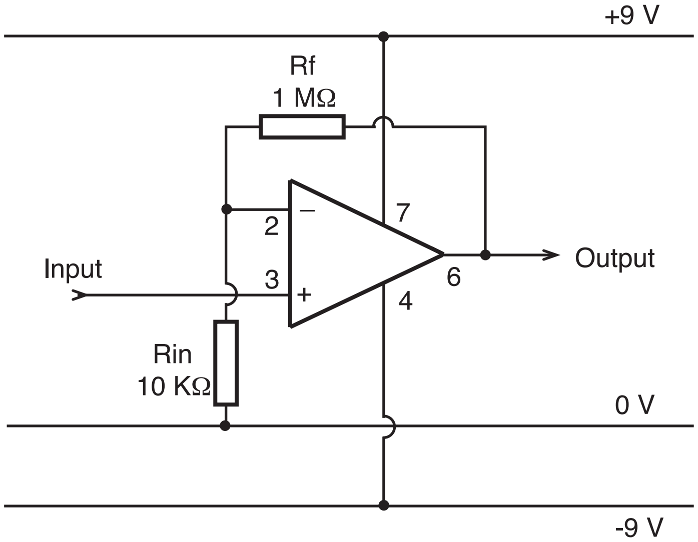
The input with the + sign is known as the non-inverting input. Any signal fed to this input will be amplified by a factor set by the gain.

The input with the - sign is known as the inverting input. Any signal fed to this input will be amplified by a factor set by the gain but inverted.

The I.C. needs a **dual polarity** power supply, i.e. both positive and negative, if it is going to amplify positive and negative inputs. The power supply needs to provide three power supply rails; +9 volts, 0 volts and -9 volts. A good way to produce this power supply is to use two 9 volt PP3 batteries connected like this.



We will be using the Op Amp as a **non-inverting** amplifier. The I.C. needs only two external resistors to make it work in this mode. They are connected like this.



These two resistors set the gain of the Op Amp. The gain of the amplifier is calculated using the formula;

$$\text{Gain (A)} = 1 + \frac{Rf}{Rin}$$

$$\text{In this case the gain} = 1 + \frac{1\ M\Omega}{10\ K\Omega}$$

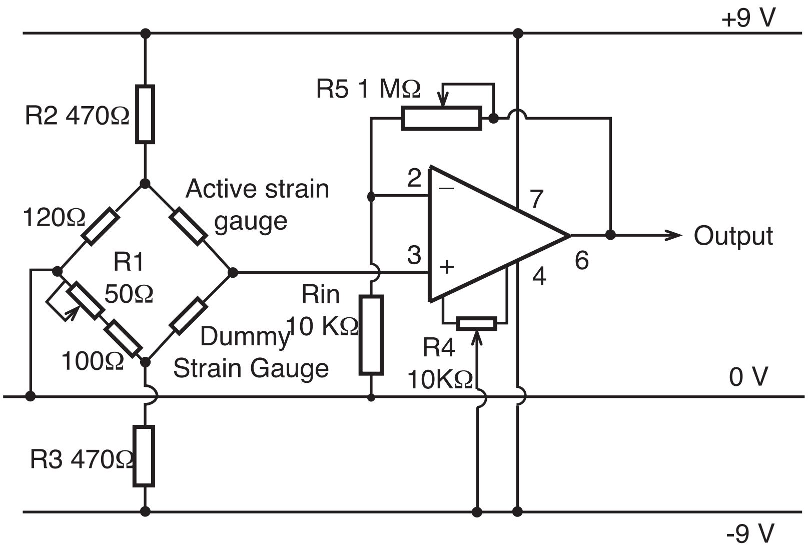
$$= 1 + \frac{1 \times 10^6}{10 \times 10^3}$$

$$= 1 + 100$$

$$= \underline{101}$$

It is possible to set the gain of the amplifier to a much higher figure than this. The maximum gain of a 741 is approximately ×100 000. It is not wise to use gains much above 100 though. This is again due to the effects of temperature. As the resistors that set the gain rise in temperature their resistance will fall. This will affect the gain of the amplifier. If the gain is too large then the effects of temperature will be very noticeable and will lead to inaccuracies and instability.

To use the Op Amp to amplify the signal from the Wheatstone bridge they are connected as shown in the diagram.



Notice the extra resistors that have been added. The variable resistor R1 allows you to balance the bridge, i.e. set the output signal to zero when no force is applied to the material.

R2 and R3 limit the amount of current that flows through the strain gauges. Too much current will cause the strain gauges to heat up a little and change their resistance.

R4 is connected to the 'offset null' pins of the I.C. This allows you to set the output of the Op amp to zero when there is no input.

R5, the feedback resistor, allows you to vary the gain of the amplifier. You can set this to calibrate the amplifier so a known input gives a desired output.

When you first test the circuit you will need to set it up. Start with no load applied to the strain gauge. Connect a voltmeter between point **B** and point **A**. Adjust R1 until the reading is 0 volts.

Next connect the voltmeter to the output of the amplifier. Adjust R4 until the output from the amplifier is 0 volts.

Now apply a load to the material that the gauge is fitted to. Check that the output from the amplifier rises positively for compressive forces and falls negatively for tensile forces. Adjusting R5 will change the amount by which the output voltage rises or falls. You should notice output voltages ranging from -200mV to +200mV.

You now have a basic system that could be used as the basis for some electronic scales. The strain gauge would need to be attached to some form of platform of your own design. This would need to apply a compressive force to the gauge when a load is ‘weighed’.

You could couple a simple meter, ideally a centre reading meter, to the output of the amplifier and then calibrate this with a scale relating to weight.

The output signal from the amplifier may need to be further amplified. This can be done by adding another non-inverting amplifier to the system. Remember it is not good practice to have an amplifier stage with a gain of more than about 100 so two stages are desirable for this reason alone.

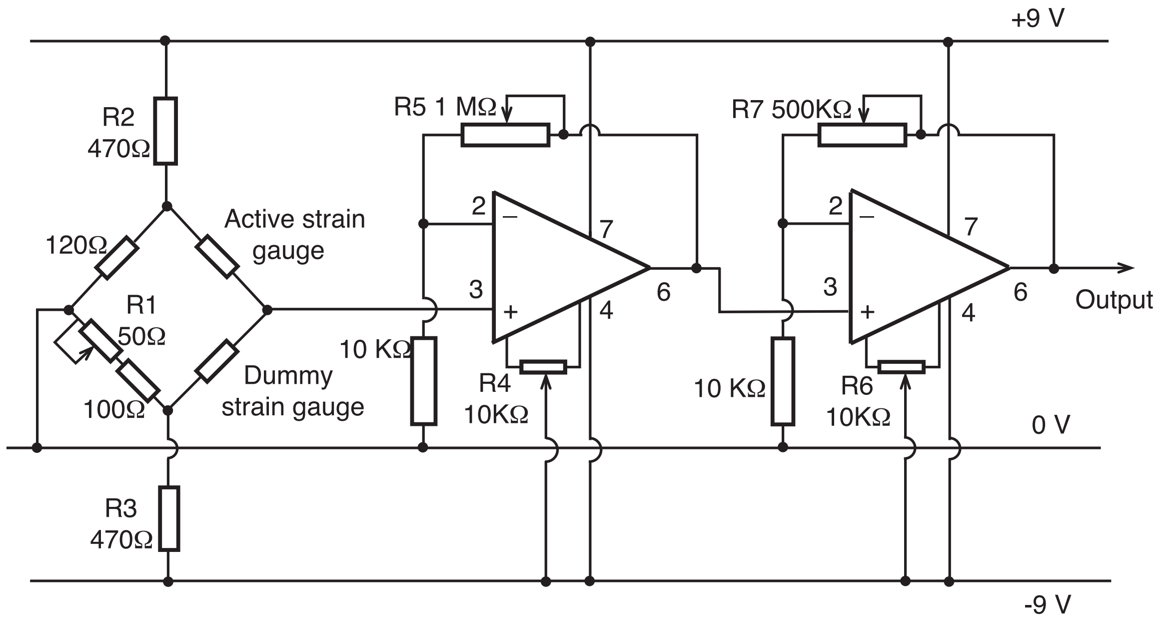
The second amplifier stage should have a gain of about 50. To find the gain of the complete system use the formula;

Gain (A) = gain1 × gain2

= 100 × 50

= <u>5000</u>

This will give you an output that ranges between -9 volts and +9 volts. You could add this stage to the simple scales circuit to increase their sensitivity. This is the circuit diagram for the two stage amplifier.



Again you need to set it up when it is complete. First connect a voltmeter between point **B** and point **A**. adjust R1 until the meter reads 0 volts.

Next connect the voltmeter to the output of the first amplifier stage. Adjust R4 until the output of the first amplifier is 0 volts.

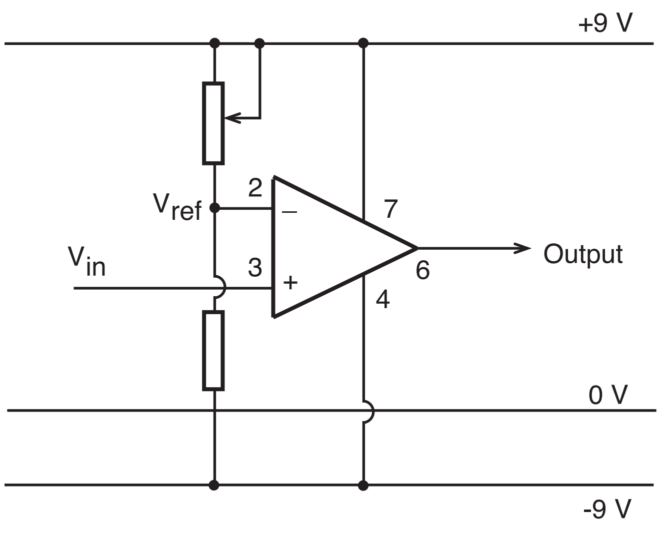
Next connect the voltmeter to the output of the second amplifier stage. Adjust R6 until the output from the second amplifier is 0 volts.

Now apply different loads to the strain gauge. Adjust R5 and R7 until the output from the second amplifier ranges between +/- 9 volts when a maximum compressive and tensile load is applied.

Now you have a usable signal to provide warnings when a maximum strain value is exceeded. This concept could be useful in providing failsafe systems for lifting equipment.
To do this you need to be able to set a maximum strain level allowed. This can be achieved by adding a further stage to the control system known as a comparator.

COMPARATORS

A comparator is basically an Op Amp with no feedback resistor. Both inputs are used. A comparator compares the two voltages that are fed to the inputs. This is the circuit diagram for a comparator.



The voltage fed to the inverting input is known as the reference voltage or Vref. The voltage that is fed to the non-inverting input is known as the input voltage or Vin.

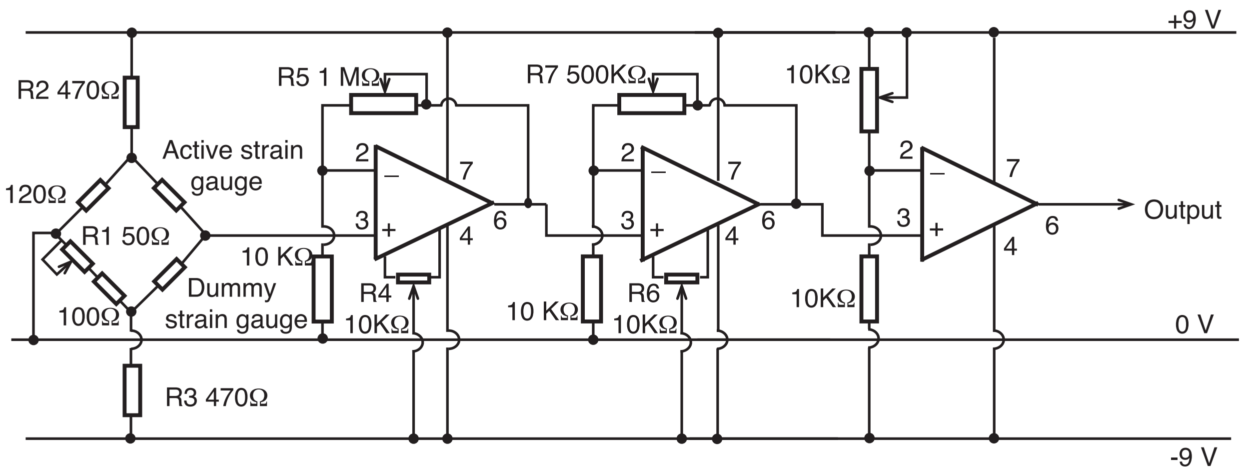
The comparator has no feedback resistor so its gain will be very high (approximately 100 000). If the input voltage is greater than the reference voltage then the difference in the two will be amplified and the output will go positive.

Because the gain is so high even a tiny difference will cause the output to rise so high that the device becomes saturated. This means that the output will rise to the + supply voltage, i.e. +9 volts.

If the input voltage falls below the reference voltage then the difference between the two will again be amplified and this time the output will go negative. Again because of the very high gain even a tiny difference will cause the device to become saturated. This means that the output will fall to -9 volts.

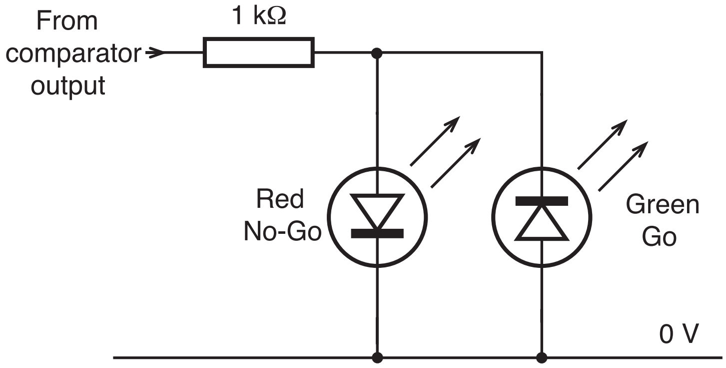
So the comparator is a simple form of analogue to digital converter. The input voltage can range anywhere between ±9 volts. The output voltage will be either high or low (+9 volts or -9 volts.) The reference voltage sets the point at which the output switches from high to low. This point is often referred to as the **threshold voltage**.

Adding a comparator to the control system means that you can cause the output to rise sharply from -9 volts to +9 volts when a maximum strain is exceeded. The point at which this happens can be set by you by adjusting the comparator reference voltage. This circuit includes the comparator.



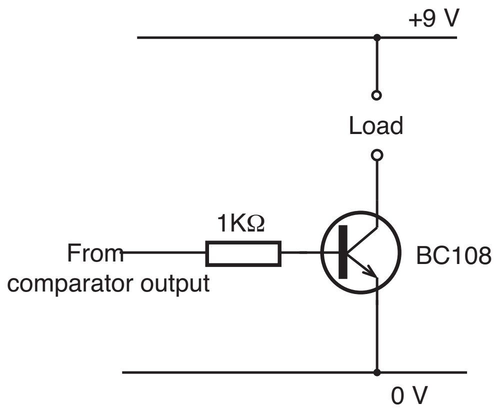
The output will be at -9 volts when no strain is applied. The output will rise to +9 volts when the input voltage to the comparator exceeds the reference voltage. (These values are theoretical. In practice the output will probably range between ±8 to 8.5 volts) This will happen when you apply a large **compressive load** to the strain gauge. Adjusting the reference voltage will change the maximum strain setting.

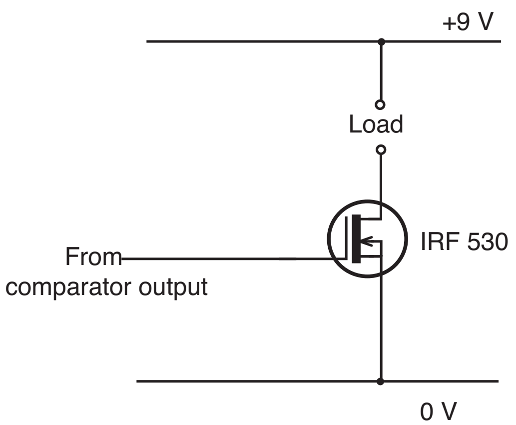
The output from this circuit could be used to give a simple warning. The output from the comparator is capable of sinking and sourcing approximately 20 mA so it will be able to drive an LED. You could connect two LEDs like this to give a go/no go indication.



When comparator output = +9 volts red LED lights
When comparator output = -9 volts green LED lights

Any higher current loads such as buzzers or sounders will need some current amplification to drive them. A Bipolar transistor or FET could be used for this.





The addition of a relay could control the power to a motor used with the lifting equipment.

When the equipment begins to lift the load, strain will be applied to the lifting arm. A strain gauge attached to the arm could sense this. If the strain increases above the maximum set limit before the load is lifted from the ground then the relay can cut the power to the motor preventing the dangerous lift from taking place.

Further improvements could include giving more visual feedback to the operator. This could be in the form of a simple meter connected to the output of the second amplifier stage, effectively combining the scales principle with the lifting equipment. This would tell the operator the weight of the load being lifted and could incorporate a ‘red line’ or danger zone.

These circuits and principles can be adapted to fit many other applications. The strain gauges in the Wheatstone bridge can be replaced by other resistive components such as LDRs and Thermistors. Using 741 Op Amps as amplifiers and comparators will allow you to improve the accuracy, stability and effectiveness of the control systems that you design.