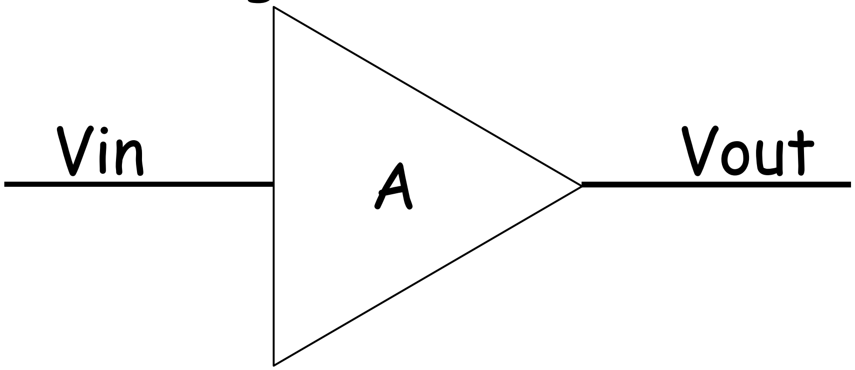
Operational Amplifiers

Electrical and Electronic Principles

Amplifier Gain

The diagram below shows an Amplifier:



A is the amplifier gain and we have the relationship:

$$Vout = A \times Vin$$

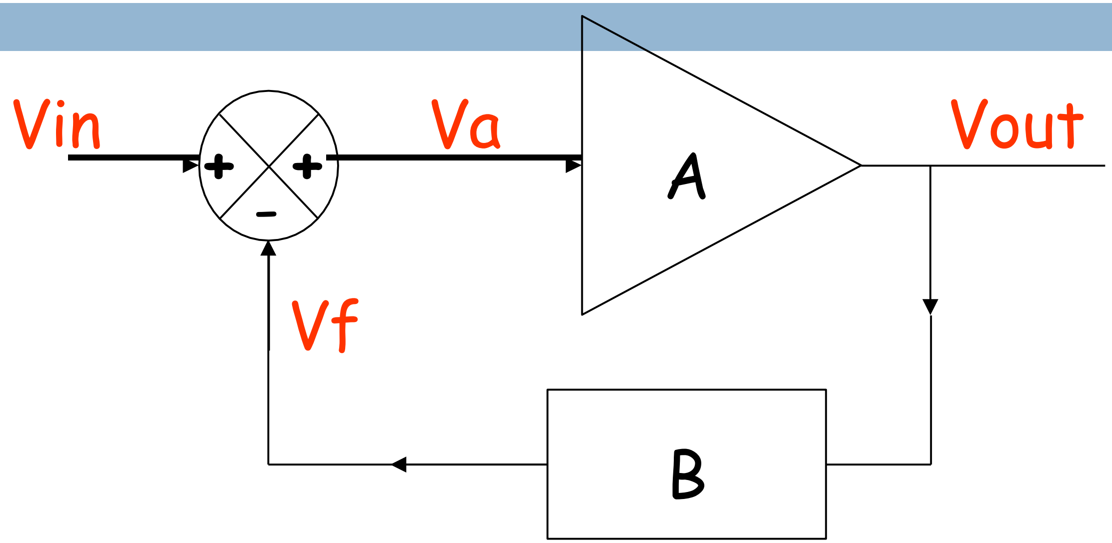
Problems with this arrangement are that:

"A" is controlled by transistors and we have little or no control over their gain. Two identical circuits will have different gains due to the tolerance in the components especially the transistor gains.

"A" may vary with:

Temperature, Supply Voltage, Aging

For the above reasons we introduce Negative Feedback (NFB) into the amplifier.



From the above we can see that:

$$Vout = A \times Va \qquad (1)$$

$$Vf = B \times Vout \qquad (2)$$

$$Va = Vin - Vf \qquad (3)$$

using (1) and (2) in (3) gives us:

$$\frac{Vout}{A} = Vin - B \times Vout \qquad Vout\left(\frac{1}{A} + B\right) = Vin$$

$$Vout\left(\frac{1 + A \times B}{A}\right) = Vin \qquad Gain = \frac{Vout}{Vin} = \frac{A}{1 + A \times B}$$

e.g.
An amplifier has a gain A = 14000 and a feedback ratio of 0.01. What is the gain?

Due to component replacement A increases by 15%. What is the new gain with feedback?

We can make certain assumptions about the gain equation –

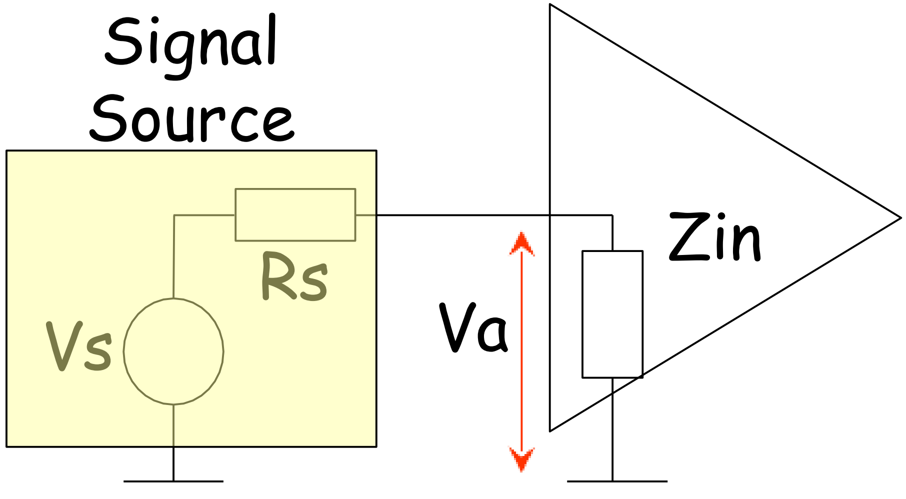
$$Gain = \frac{A}{1 + A \times B}$$

if A is large then $A \times B \rangle\rangle 1$ and the gain becomes:

$$Gain = \frac{A}{A \times B} = \frac{1}{B}$$ i.e. independent of A

Therefore we may wish to look for an amplifier with a very large gain.

Input Impedance (Resistance)



Va is the voltage that appears on the input of the amplifier and will be amplified. Rs is the source resistance and cannot be altered.

Note Va does not equal Vs

$$Va = \frac{Vs \times Zin}{Rs + Zin}$$

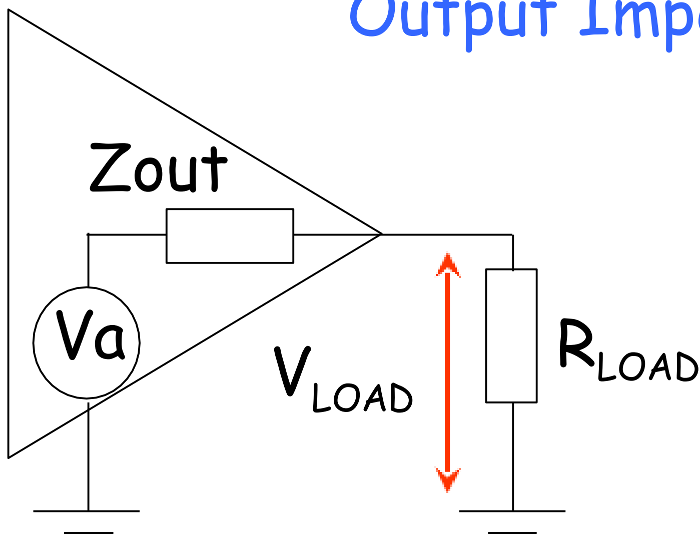
How can we make $Va = Vs$?

Zin should be as large as possible so that $Zin + Rs \approx Zin$

If this is so then $Va = Vs$

Therefore we may wish to look for an amplifier with a very large input impedance.

Output Impedance (Resistance)



V_{LOAD} is the voltage that appears on the output of the amplifier. R_{LOAD} is the load resistance and cannot be altered.

Note V_{LOAD} does not equal Va (the input amplified)

$$V_{LOAD} = \frac{Va \times R_{LOAD}}{R_{LOAD} + Zout}$$

How can we make $Vload = Va?$

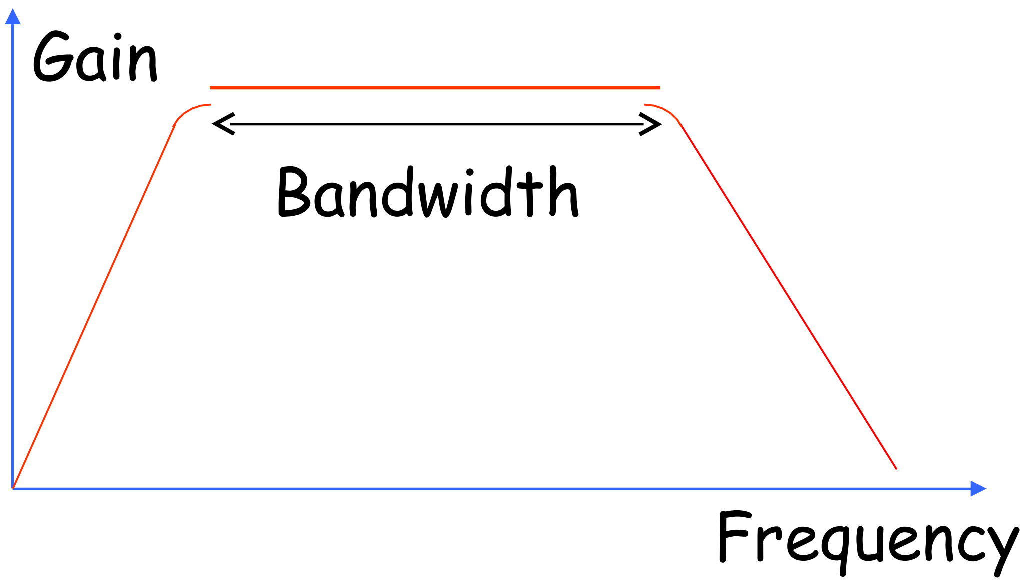
Zout should be as small as possible so that $Zout + R_{LOAD} \approx R_{LOAD}$

If this is so then $V_{LOAD} = Va$

Therefore we may wish to look for an amplifier with a very small output impedance.

Bandwidth

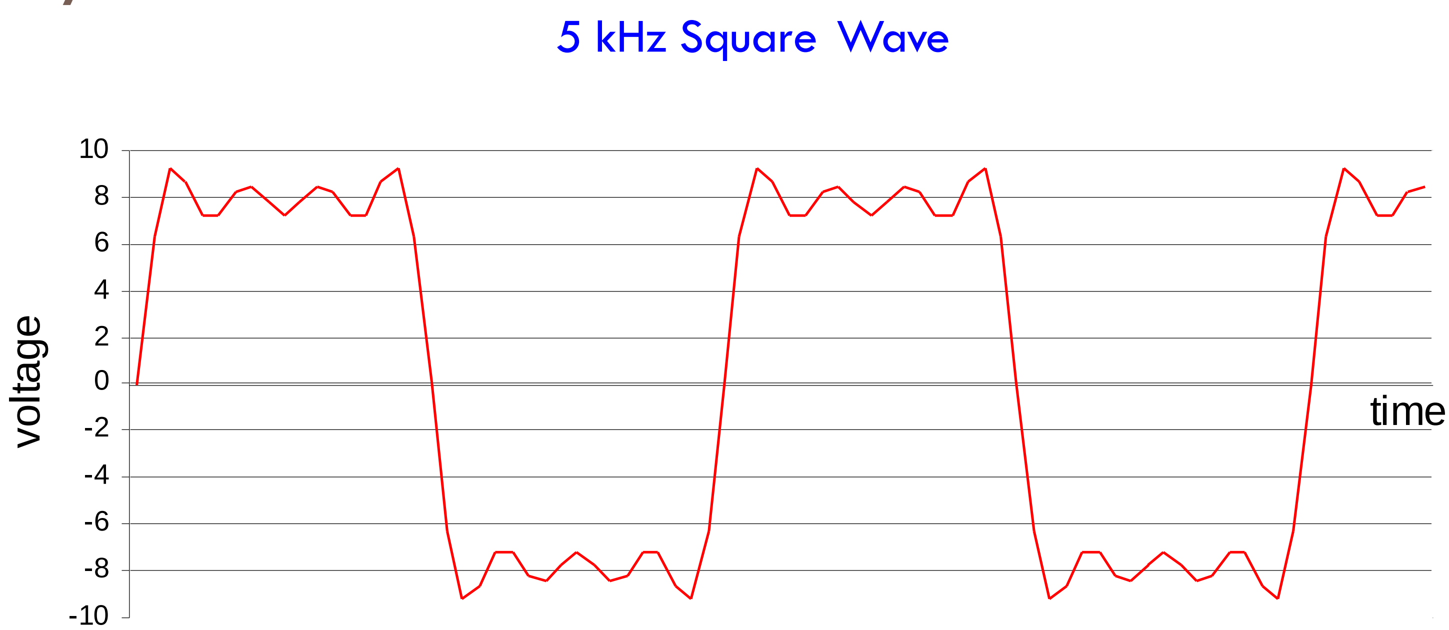
Bandwidth :- the range of frequencies over which the amplifiers gain remains constant.



If we wish to amplify a complex periodic waveform such as a square wave then Fourier Analysis tells us that the wave is made up of a large number of sinusoidal waves of different frequencies.

e.g. A 5 kHz square wave will be made up of a wave at 5 kHz, another at 15 kHz another at 25 kHz, 35 kHz etc.

Very soon the harmonics as they are called reach high frequency values and unless the bandwidth is large we will start to deform the waveform. The plot below is of the 5 kHz square wave with only the fundamental and first 3 harmonics.



Therefore we may wish to look for an amplifier with a very large bandwidth.

Operational Amplifiers

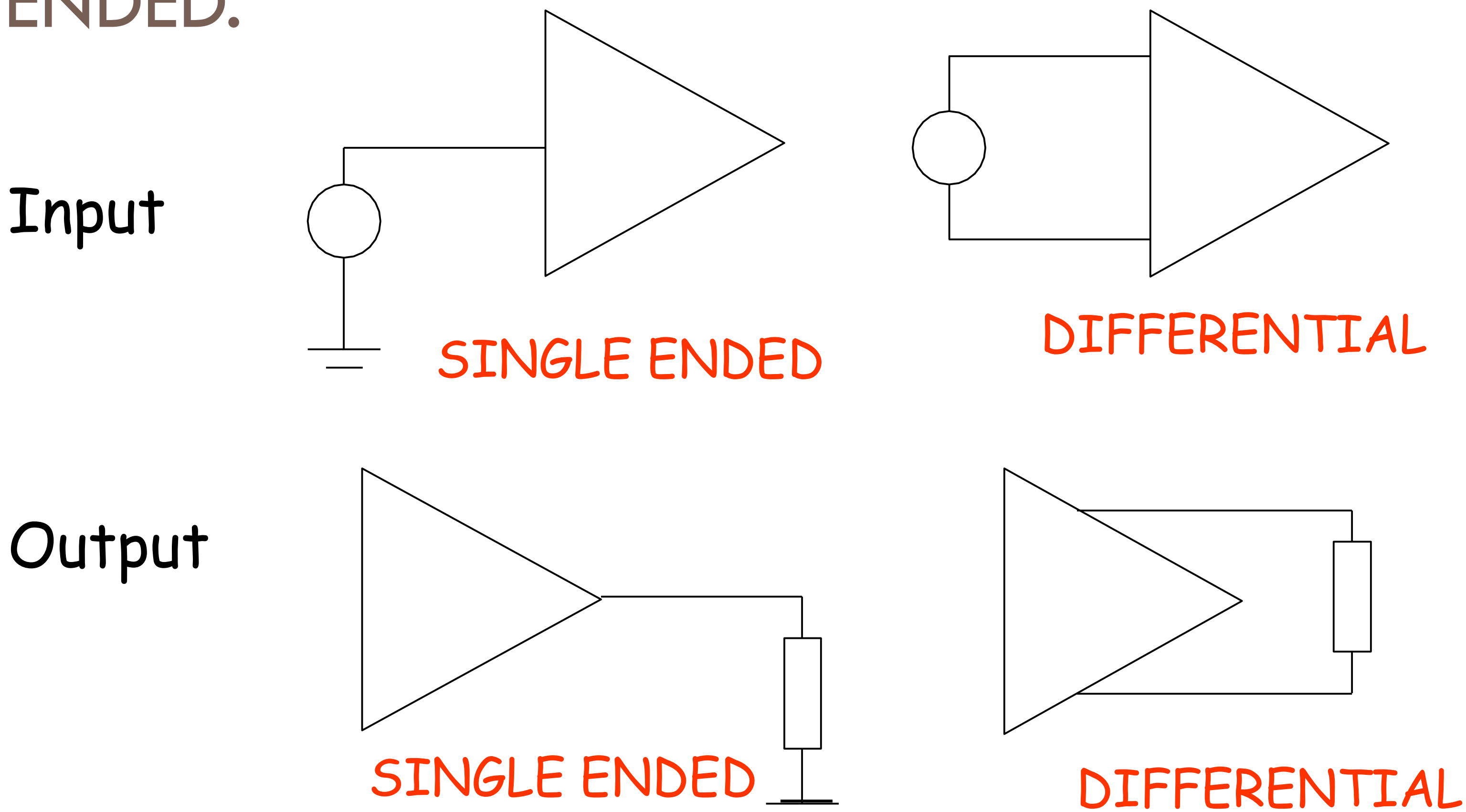
These are amplifiers with the following special characteristics.
NOTE they are theoretical tools.

Gain	infinite.
Input Resistance	infinite
Output Resistance	zero
Bandwidth	infinite

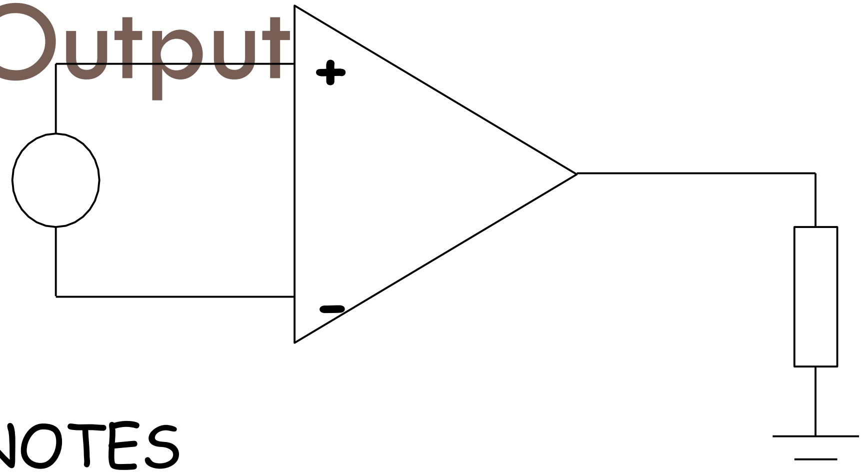
In practice with modern I.C. technology we can end up with values for the parameters that are close to the ideal:

Gain	$> 10^6$.
Input Resistance	$> 10^{12}\ \Omega$
Output Resistance zero	$< 10\ \Omega$
Bandwidth	$> 10^6$ Hz

The form that the amplifier can take will depend upon the nature of the input and output connections. Input and outputs can be either DIFFERENTIAL or SINGLE ENDED.



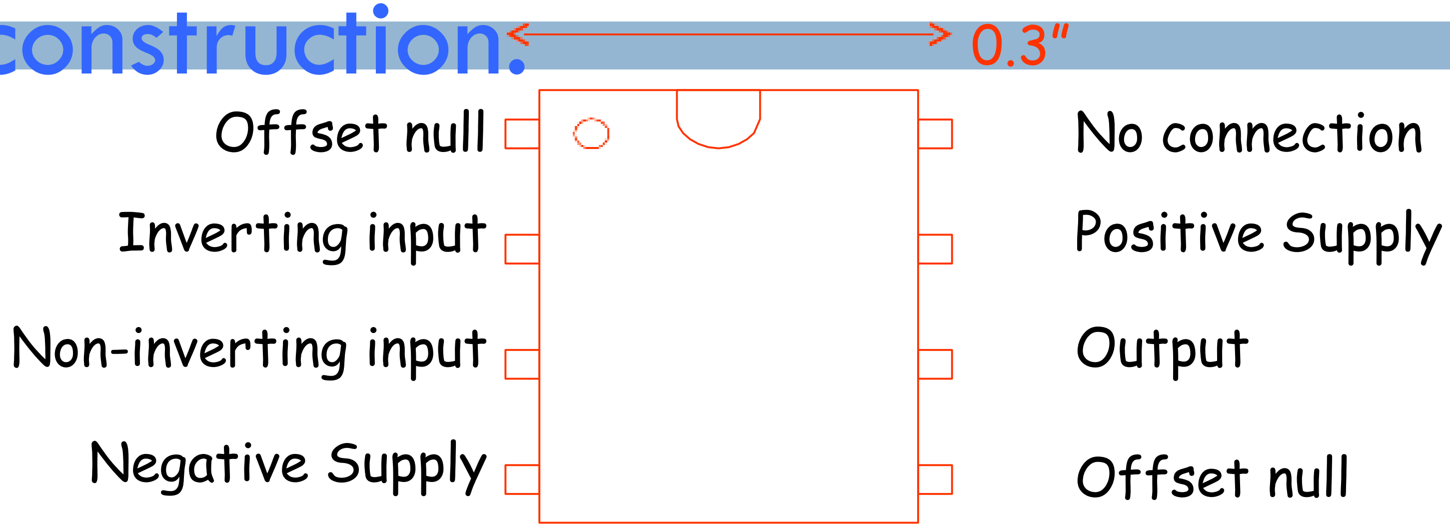
The most common configuration is Differential Input, Single Ended Output



NOTES

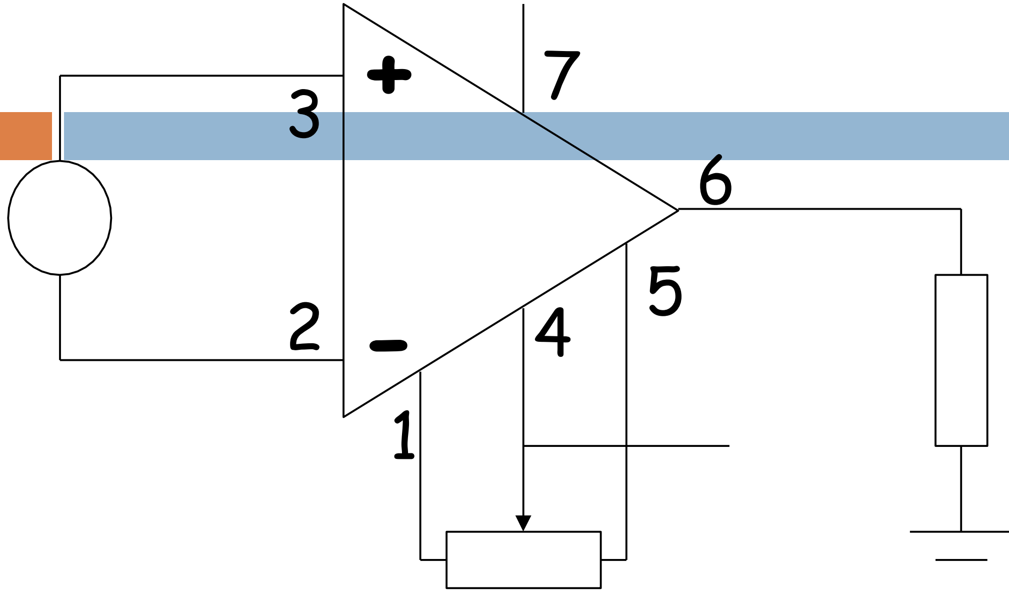
- Power supply connections are not normally shown but usually take the form of +Vs, 0v and -Vs, e.g. +12V, 0V, -12V.
- The positive + terminal is the non-inverting input. A signal on this input will not be phase shifted when amplified.
- The negative - terminal is the inverting input. A signal on this input will be phase shifted by 180° when amplified.

Typical I.C. construction:

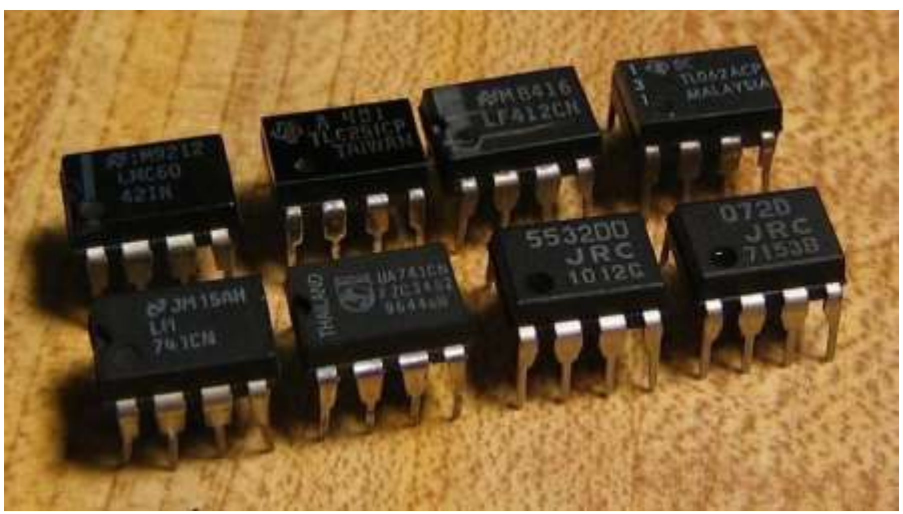


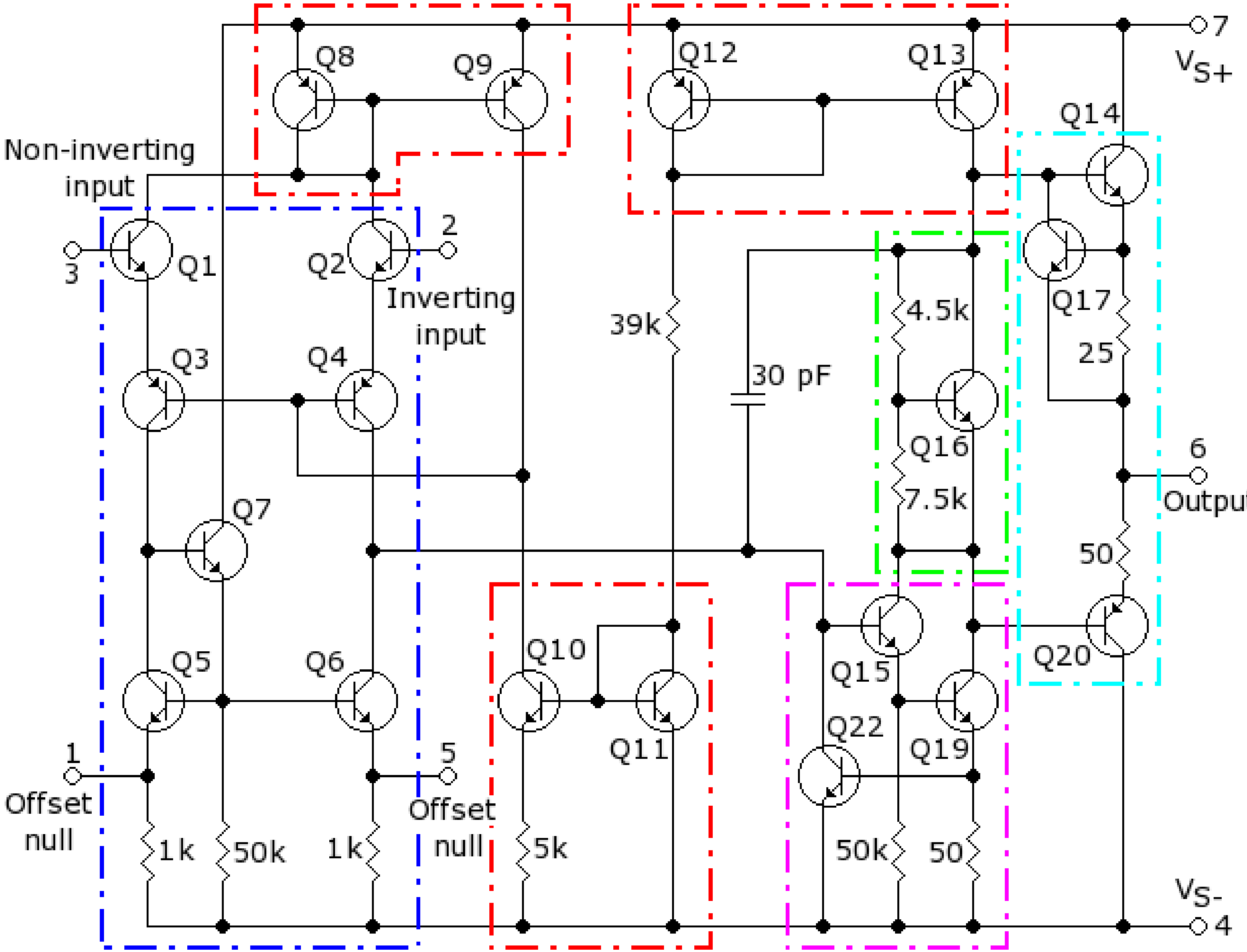
Offset Null

The input to an Op-Amp is differential and in practice this means that there are two parallel input stages. The output from these stages are then subtracted then further amplified. The gains of these two stages can be balanced using the offset null adjustment. See over the page:



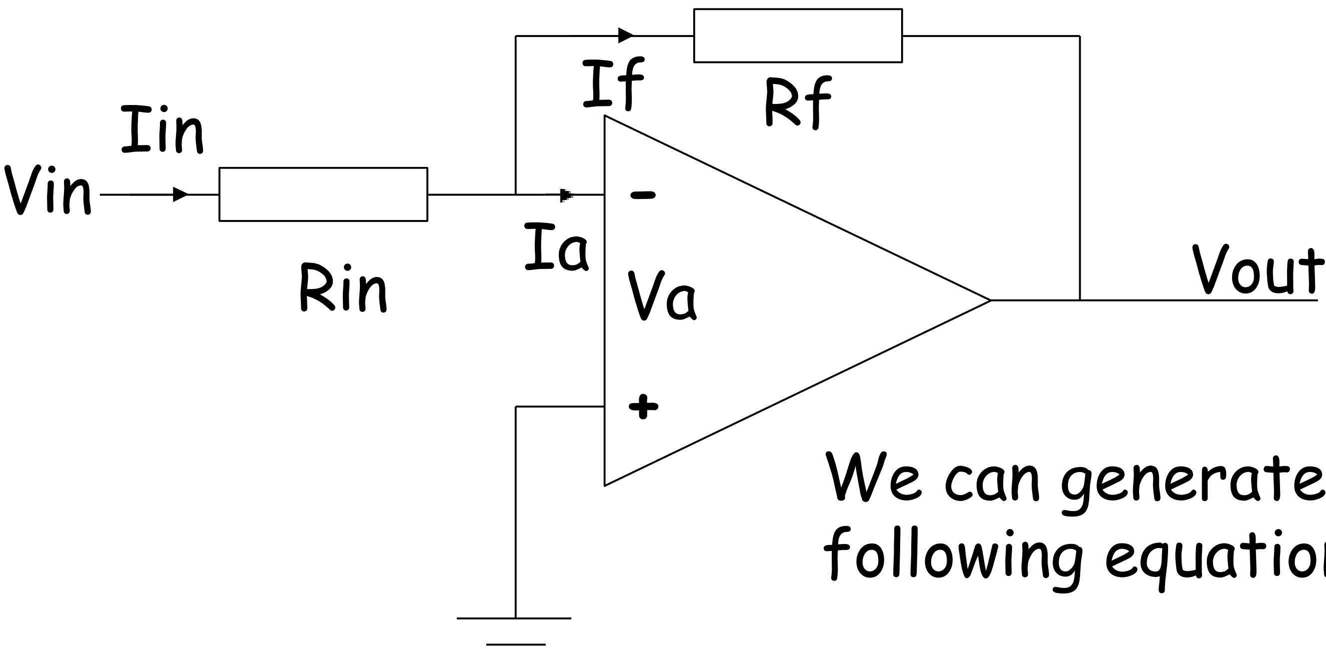
taken to zero and the potentiometer is adjusted to give zero ou





Non-inverting
input
3
Q1
Q2
2
Inverting
input
Q3
Q4
Q5
Q6
Q7
Q8
Q9
Q10
Q11
Q12
Q13
Q14
Q15
Q16
Q17
Q19
Q20
Q22
1
Offset
null
5
Offset
null
1k
50k
1k
5k
39k
30 pF
4.5k
7.5k
25
50
50k
50
7
VS+
6
Output
VS-
4

INVERTING AMPLIFIER



We can generate the following equations:

$$Iin = \frac{Vin - Va}{Rin} \qquad If = \frac{Va - Vout}{Rf} \qquad Iin = Ia + If$$

Combining these gives us:

$$\frac{Vin - Va}{Rin} = Ia + \frac{Va - Vout}{Rf}$$

This is true for any amplifier.

But this is an op-amp and therefore we can make certain assumptions…

1. *Va = 0. This is because the gain is very large and therefore Va will be very small.*
2. *Ia = 0. This is because the input impedance is very large and therefore Ia will be very small.*

We can therefore rewrite the equation:

$$\frac{Vin}{Rin} = \frac{-Vout}{Rf} \quad \text{or} \quad Gain = \frac{Vout}{Vin} = \frac{-Rf}{Rin}$$

The minus sign indicates that this is an inverting amplifier.

This set up is called a Virtual Earth Amplifier as the amplifier input terminal (-) is at earth potential as the + input is at earth.

Note

The gain is determined purely by the ratio of two resistors. This often means that we will not be able to directly calculate resistor values. We may need to select one and calculate the other.

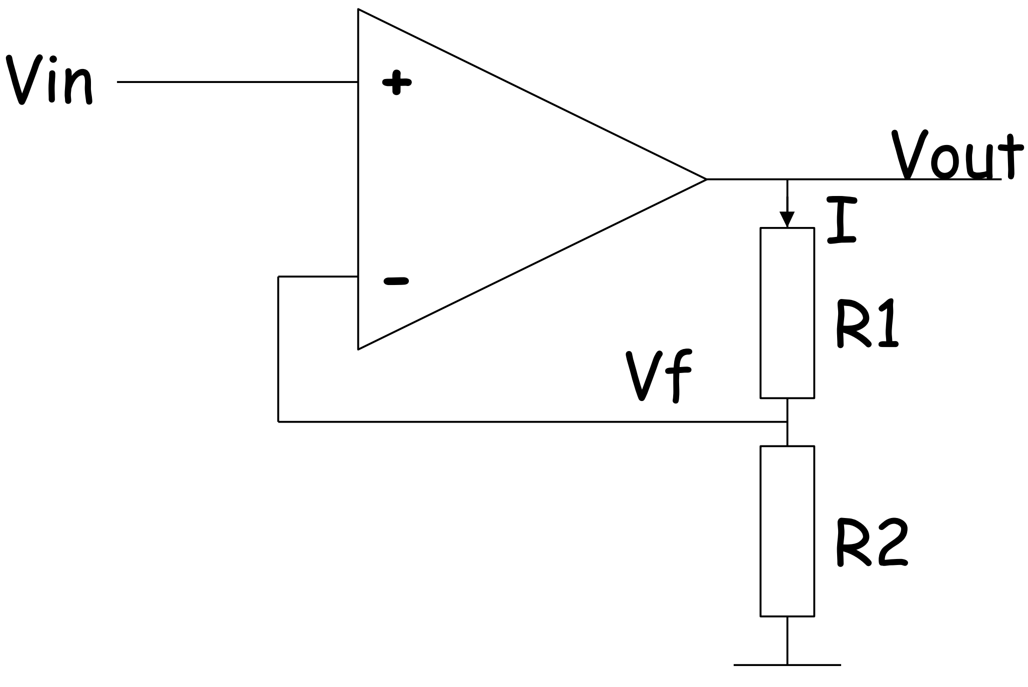
The value of resistors used around op-amp circuits tend to be no lower than

1 kΩ and no bigger than 10 MΩ.

Design an amplifier that has a variable gain from -10 to -50.

(use a 100KΩ variable resistor)

NON-INVERTING AMPLIFIER



The current I flows through both resistors as no current flows into the op-amp (assumption 2)

$$I = \frac{Vout}{R1 + R2}$$ from which $$Vf = VR2 = I \times R2 = \frac{Vout \times R2}{R1 + R2}$$

But Vf = Vin as the difference in input voltages is zero (assumption 1), so

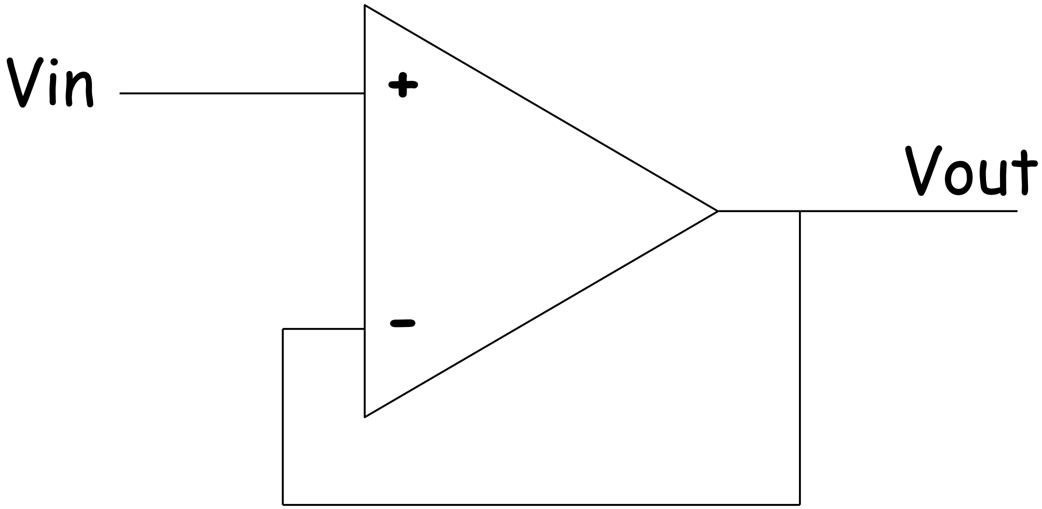
$$Vin = \frac{Vout \times R2}{R1 + R2}$$

or

$$Gain = \frac{Vout}{Vin} = \frac{R1 + R2}{R2} = 1 + \frac{R1}{R2}$$

Design an amplifier that has a variable gain from 15 to 30. (use a 100KΩ variable resistor)

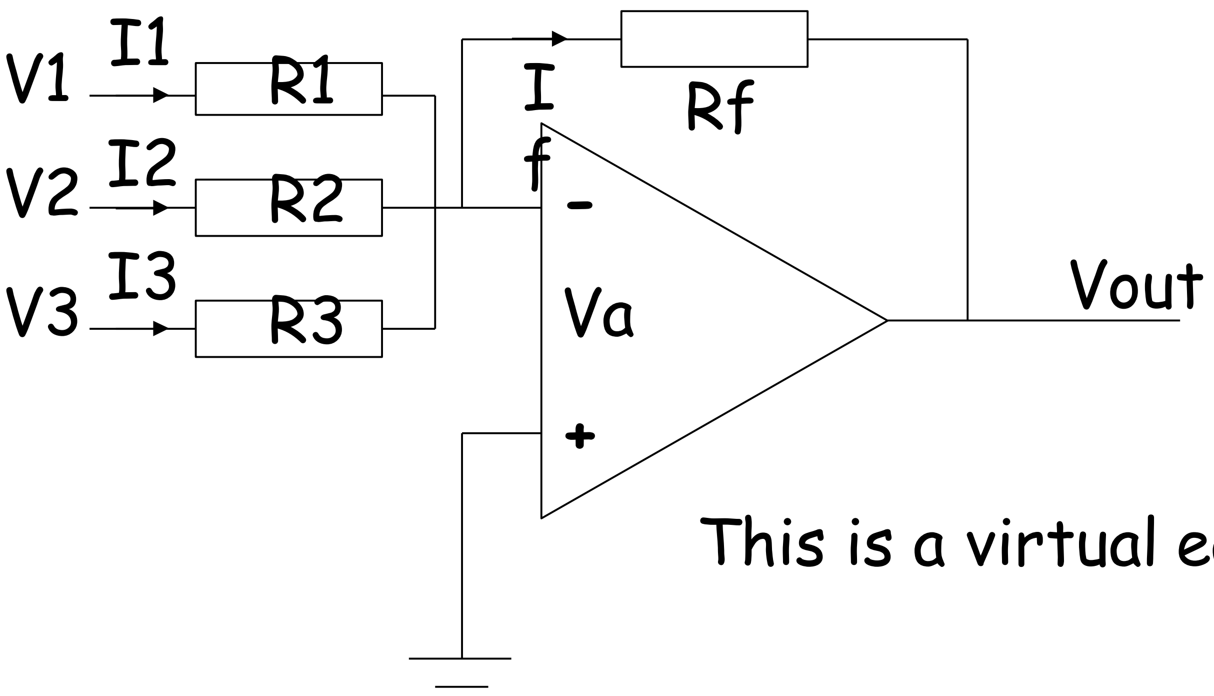
UNITY BUFFER



In the circuit Vout = Vin

- what is the purpose of this circuit?

SUMMING AMPLIFIER (Inverting)



This is a virtual earth amplifier.

$$I1 = \frac{V1}{R1} \qquad I2 = \frac{V2}{R2} \qquad I3 = \frac{V3}{R3} \quad \text{and} \quad If = \frac{-Vout}{Rf}$$

Using Kirchhoff we can say:

$$If = I1 + I2 + I3$$

$$\frac{-Vout}{Rf} = \frac{V1}{R1} + \frac{V2}{R2} + \frac{V3}{R3}$$

If R1 = R2 = R3 = Rin

$$Vout = \frac{-Rf}{Rin}(V1 + V2 + V3)$$

If Rin = Rf

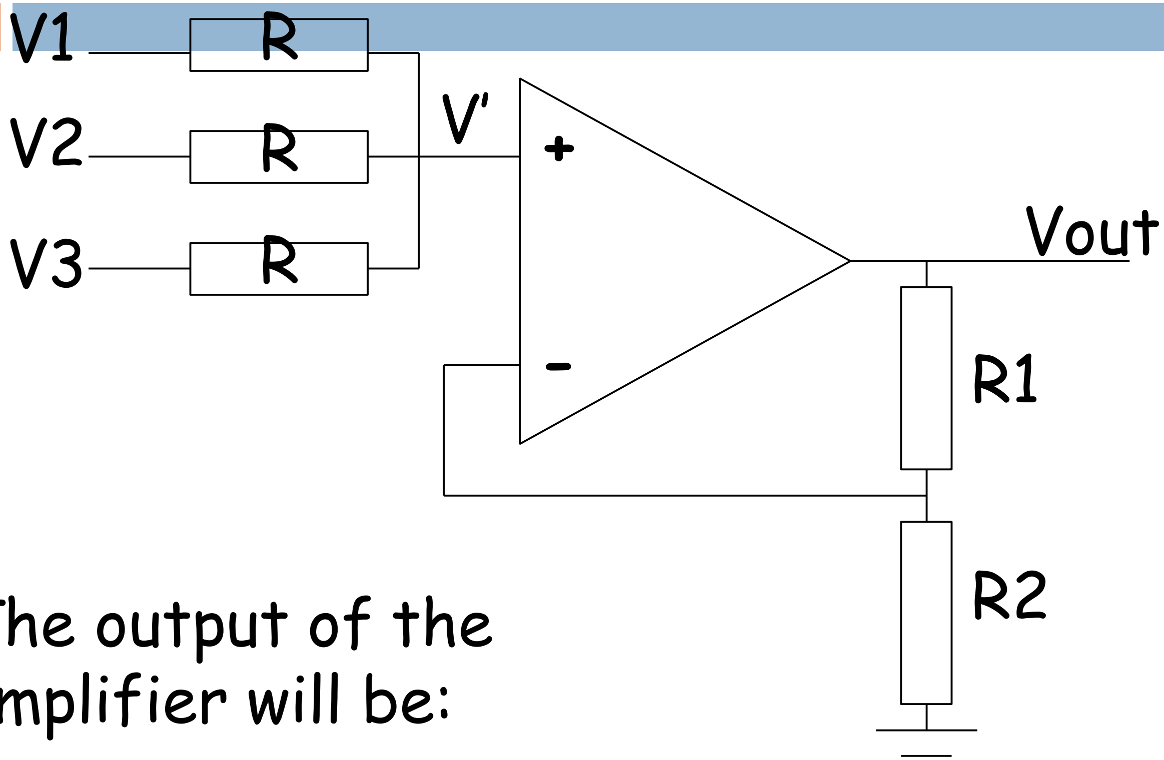
$$Vout = -(V1 + V2 + V3)$$

Notes:

2. If an input is negative it will be subtracted
3. Weighting can be applied to inputs by altering the value of the input resistance – if R1 was half the value of the other input resistors we would have:

$$Vout = -(2 \times V1 + V2 + V3)$$

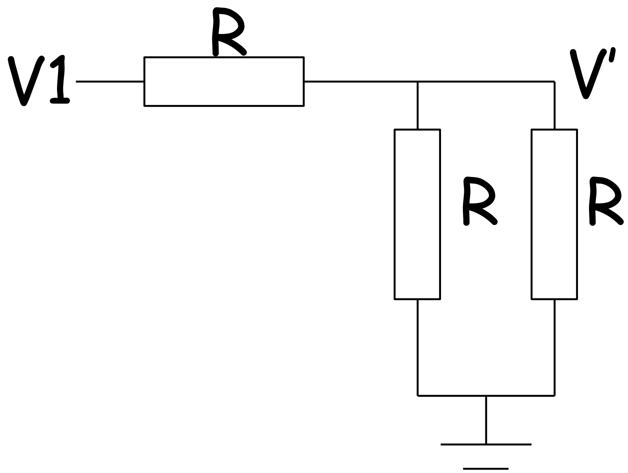
SUMMING AMPLIFIER (Non-inverting)



The output of the amplifier will be:

$$Vout = \left(1 + \frac{R1}{R2}\right) \times V'$$

What does V' equal?
- Use superposition theory



$$V' = \frac{V1 \times R/2}{R + R/2} = \frac{V1}{3}$$

The same is true for the other inputs so we can say:

$$V' = \frac{V1}{3} + \frac{V2}{3} + \frac{V3}{3} = \frac{1}{3}(V1 + V2 + V3)$$

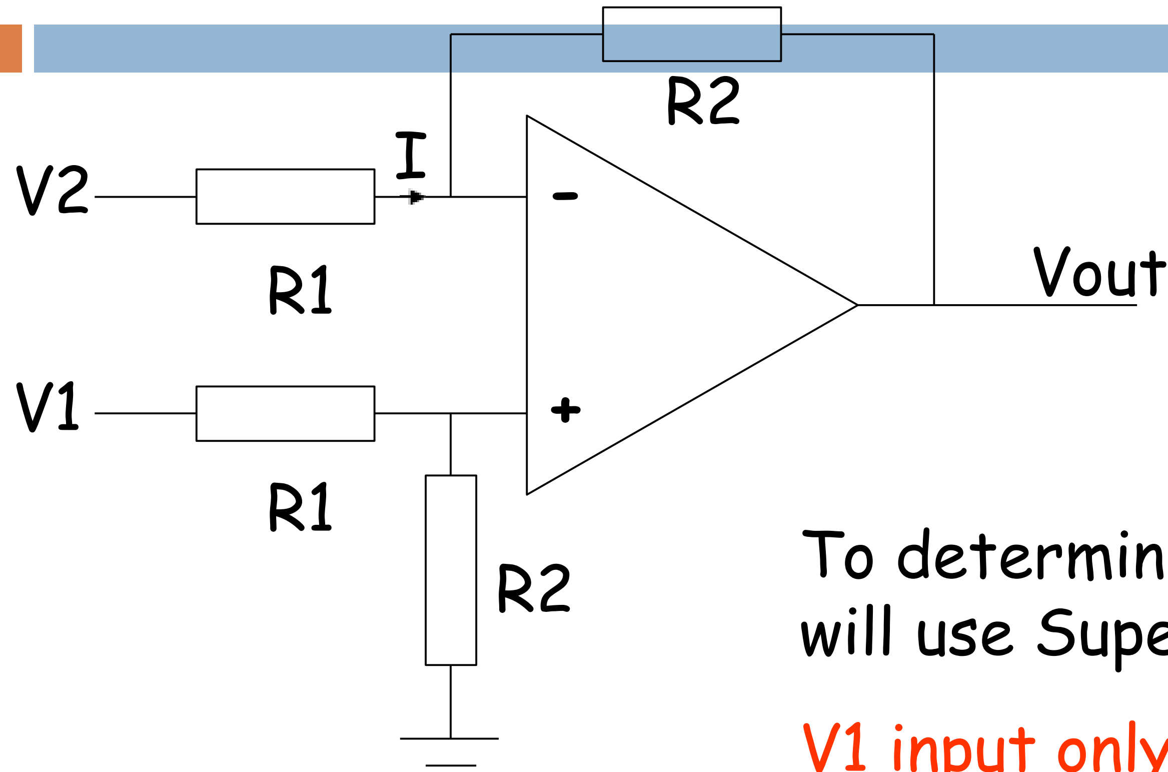
if the gain is set to 3 then:

$$Vout = V1 + V2 + V3$$

What would we get if –

V1 resistor = R
V2 resistor = 2R
V3 resistor = 3R?

SUBTRACTOR (DIFFERENCE) AMPLIFIER



To determine the output we will use Superposition.

V1 input only V2 = 0

We have a non inverting amplifier with a gain of:

$$Gain = 1 + \frac{R2}{R1} = \frac{R1 + R2}{R1}$$

The voltage appearing on the + input V+ is equal to:

$$V+=\frac{R2}{R1+R2}\times V1$$

The output is therefore input times gain:

$$Vout=\frac{R1+R2}{R1}\times\frac{R2}{R1+R2}\times V1=\frac{R2}{R1}V1$$

V2 input only V1 = 0

The V+ input will be at 0v and the amplifier will act as an inverting amplifier.

$$Gain=\frac{-R2}{R1}$$

The output will therefore be:

$$Vout=\frac{-R2}{R1}\times V2$$

Combining these gives us the overall output equation:

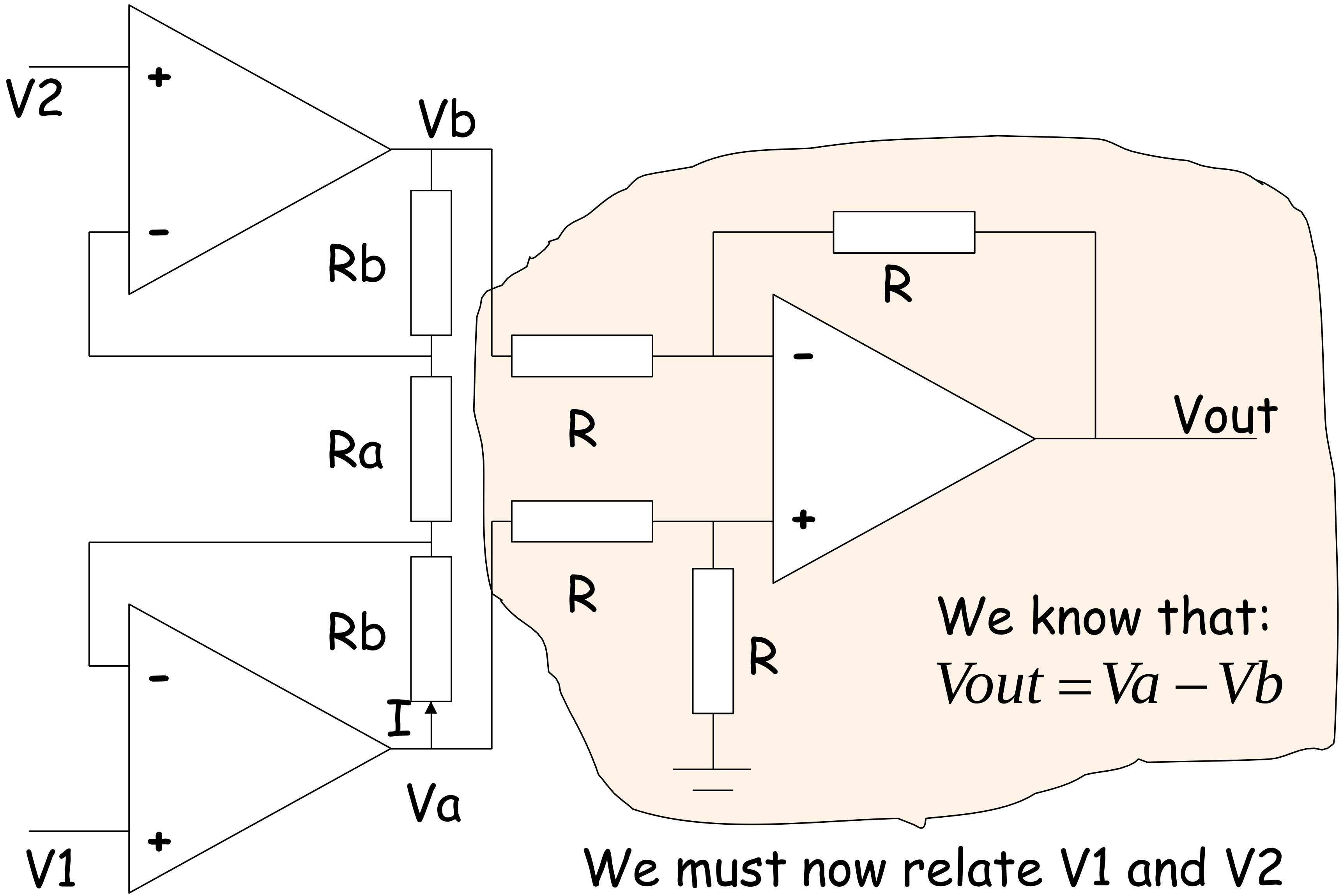
$$Vout = \frac{R2}{R1} \times V1 - \frac{R2}{R1} \times V2 = \frac{R2}{R1} \times (V1 - V2)$$

This circuit will take the difference between two inputs and amplify it by a factor R2/R1.

This circuit has two limitations:

- To alter the gain we need to simultaneously vary two resistors e.g. both values of R2.
- The input resistance to the amplifier is not very large $\approx$ R1+R2.

To overcome these limitations we use an Instrumentation Amplifier shown on the next slide:



We know that:

$$Vout = Va - Vb$$

We must now relate V1 and V2 to Va and Vb.

We can write the following equation for I

$$I = \frac{Va - V1}{Rb} = \frac{V1 - V2}{Ra} = \frac{V2 - Vb}{Rb}$$

$$\frac{Va - V1}{Rb} = \frac{V1 - V2}{Ra} \qquad \frac{V1 - V2}{Ra} = \frac{V2 - Vb}{Rb}$$

$$Va = \frac{Rb}{Ra}(V1 - V2) + V1 \qquad -Vb = \frac{Rb}{Ra}(V1 - V2) - V2$$

Adding $$Va - Vb = 2\frac{Rb}{Ra}(V1 - V2) + V1 - V2$$

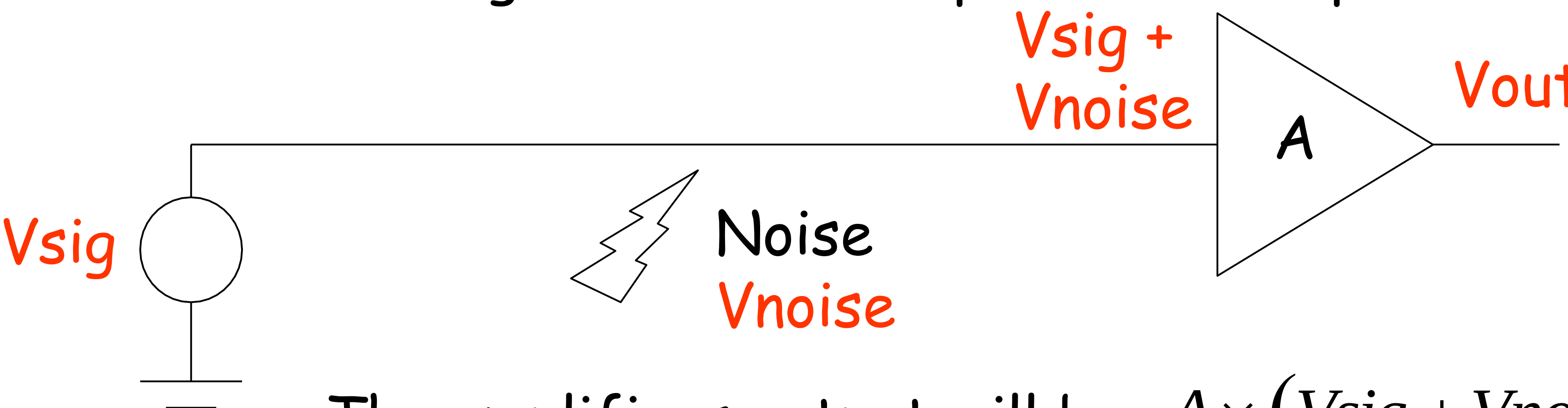
This gives us: $$Vout = \left(\frac{2Rb}{Ra} + 1\right) \times (V1 - V2)$$

The gain equals $\frac{2Rb}{Ra} + 1$ and can be controlled by a single resistor Ra.

The input impedance of the amplifier is very large as it is the actual input impedance of the op-amp.

Use of differential amplifiers.

The diagram below shows a sensor whose voltage output is transmitted along a transmission path to an amplifier.



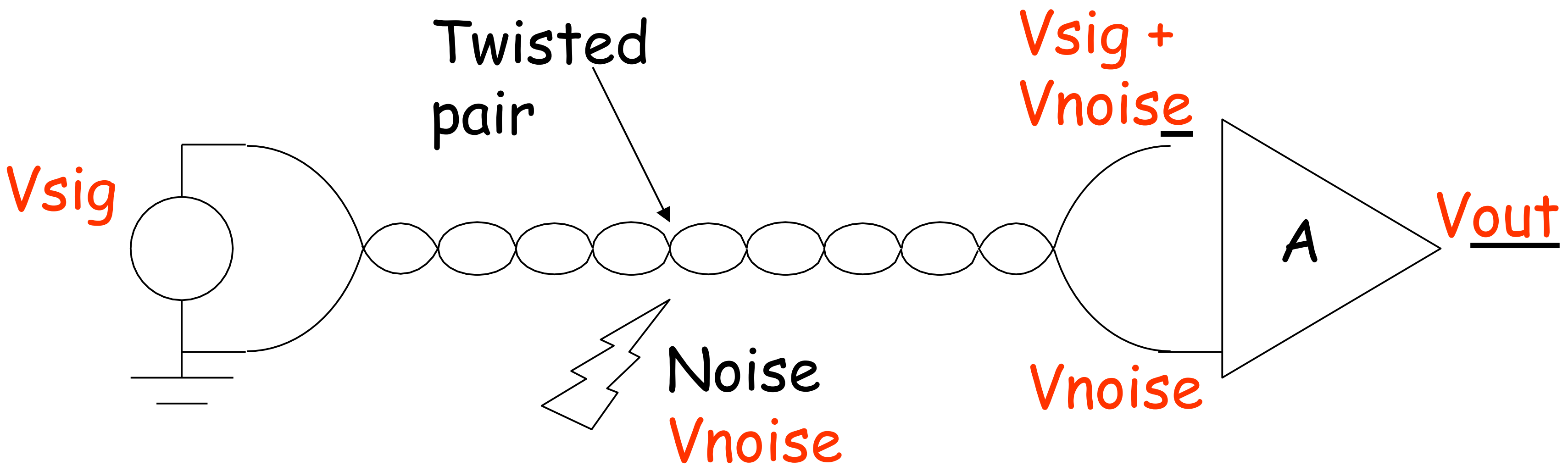
The amplifiers output will be $A \times (Vsig + Vnoise)$

Of which $A \times Vsig$ $A \times Vnoise$

Desired Undesired

Often Vnoise will be relatively large and may swamp the actual signal.

How can this be overcome?
Use a differential amplifier (subtractor).



The twisted pair ensures that each transmission path experiences the same noise and the same quantity of noise.

The amplifier output is the difference in the input times the gain.

$$Vout = A \times (Vsig + Vnoise - Vnoise)$$

This is $Vout = A \times Vsig$ (desired)

In theory we have the ability to remove any signal which appears on both inputs – i.e. a common input or a common mode input.

In practice an amplifier will amplify a common mode input and so a differential amplifier with inputs V1 and V2 will have an output given by:

$$Vout = Ad \times (V1 - V2) + Ac \times \left(\frac{V1+V2}{2}\right)$$

Differential gain

Differential input

- Common mode gain

Average input

- The measure of an amplifier to reject common mode inputs is:
  - the Common Mode Rejection Ratio (CMRR)

and is given by: $CMRR = \frac{Ad}{Ac}$

normally expressed in dB $CMRR = 20 \times \log\left(\frac{Ad}{Ac}\right)$

The larger the CMRR the better the amplifier.

Ideal op-amp CMRR value is infinity

Example.

An amplifier has a differential gain of 500 and a CMRR of 85 dB. A signal from a thermocouple has the value of 7.25mV and during transmission picks up 0.5V noise. What will be the output of the amplifier?

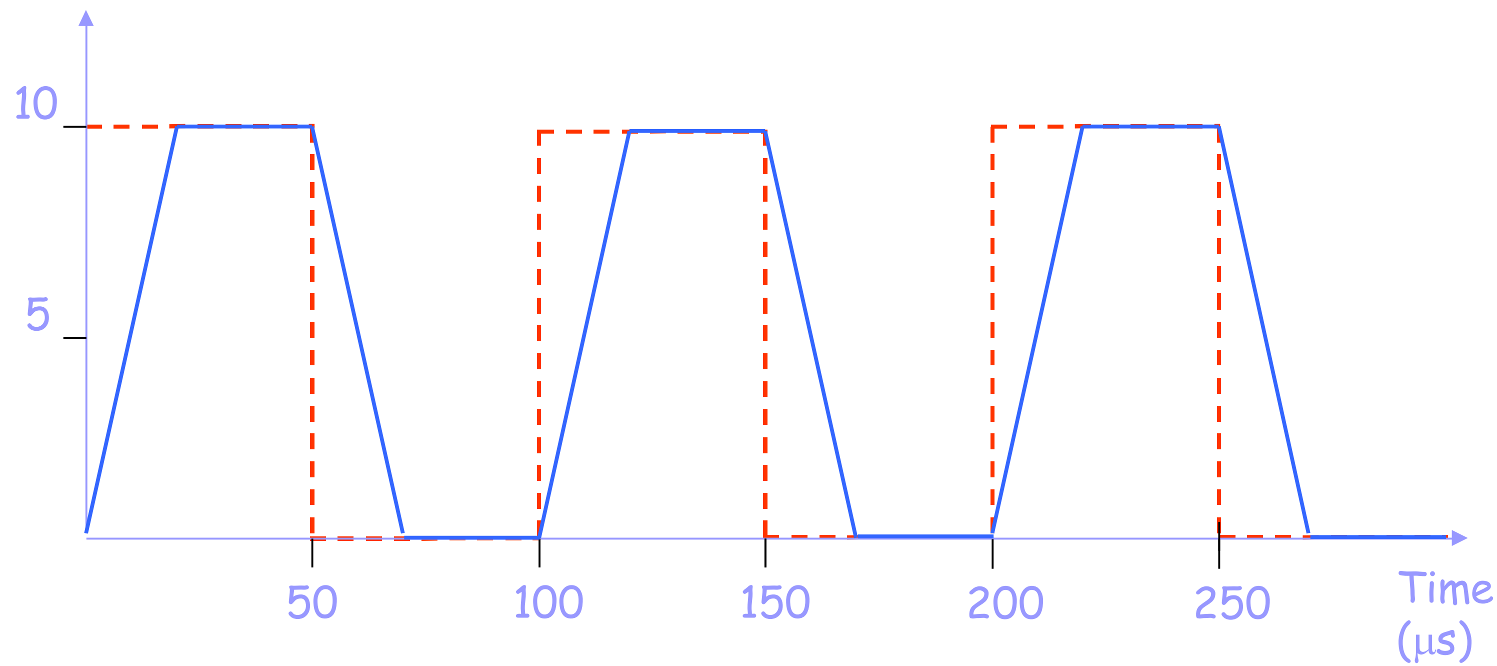
Slew Rate.

If the input to an amplifier changes rapidly then the output needs to do the same. In practice the rate at which the output can change is limited by the quality of the amplifier (linked to its bandwidth).

The measure of the maximum rate of change is called the slew rate and is measured in volts per microsecond V/μs.

An inexpensive op-amp (741) has a value of 0.5 V/μs.

Consider the effects on the output of an amplifier when the input is a square wave of various frequencies.
The amplifier output should be switching between 0V and 10V.

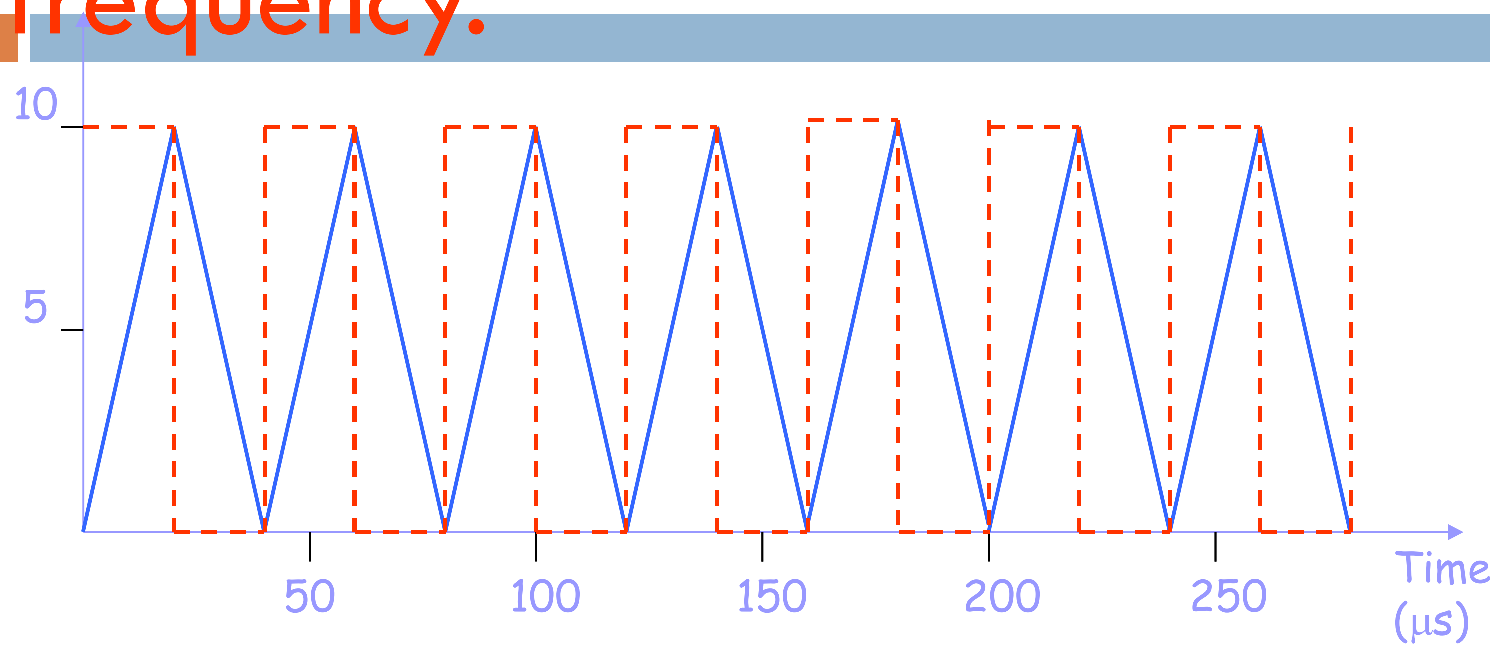


The input is at 10 kHz – it has a period of 100 μs (50 μs on 50 μs off)

The output takes 20 μs to rise and 20 μs to fall giving rise to the output shown.

There is some distortion but the signal is still recognisable.

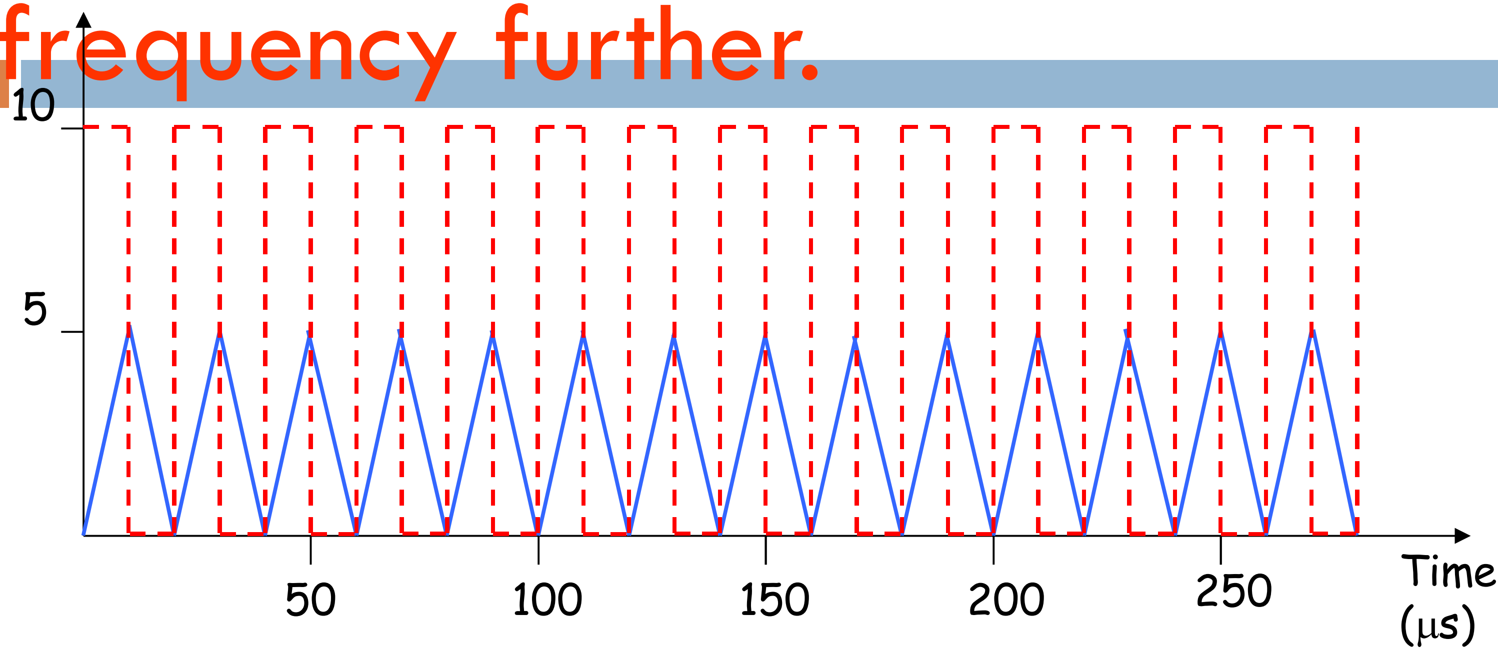
Let us increase the frequency.



The input is at 25 kHz – it has a period of 40 μs (20 μs on 20 μs off)

The output is distorted enough to make the square wave output appear to be a triangular wave.

Let us increase the frequency further.



The input is at 50 kHz – it has a period of 20 μs (10 μs on 10 μs off)

It can be seen that above a certain frequency the distortion to the waveform is excessive. The only way of overcoming this is to use an op-amp with a larger slew rate.

A 351 op-amp has a slew rate of 35V/μs and this would mean that instead of taking 20μs to rise from 0 to 10V with the 741, it would take only 0.29μs.

The larger the Slew Rate the better the amplifier.

Ideal op-amp Slew Rate value is infinite