

## Electronic Circuits

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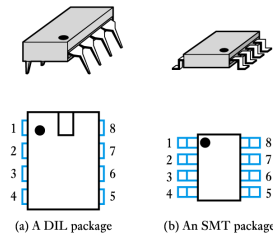
## Operational amplifiers

- Introduction
- An ideal operational amplifier
- Basic operational amplifier circuits
- Other useful circuits
- Real operational amplifiers
- Selecting component values
- Effects of feedback on op-amp circuits

## Introduction

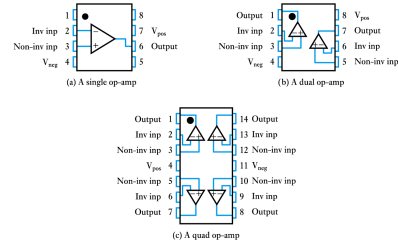
- **Operational amplifiers (op-amps)** are among the most widely used building blocks in electronics

- they are integrated circuits (ICs)
- often DIL or SMT



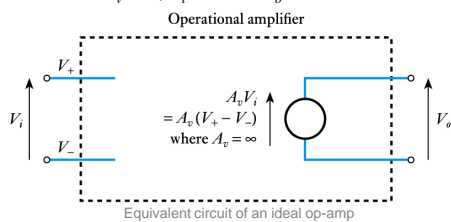
## Introduction (contd.)

- A single package will often contain several op-amps



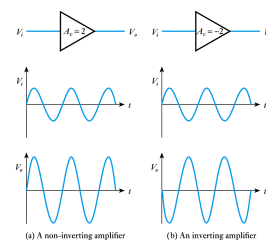
## An ideal operational amplifier

- An *ideal* op-amp would be an ideal voltage amplifier and would have:  $A_v = \infty$ ,  $R_i = \infty$  and  $R_o = 0$



## Basic operational amplifier circuits

- Inverting and non-inverting amplifiers



### Basic operational amplifier circuits (contd.)

- When looking at feedback we derived the circuit of an amplifier from 'first principles'
- Normally we use standard '**cookbook**' circuits and select component values to suit our needs
- In analysing these we normally assume the use of ideal op-amps
  - in demanding applications we may need to investigate the appropriateness of this assumption
  - the use of ideal components makes the analysis of these circuits very straightforward

### Basic operational amplifier circuits (contd.)

#### A non-inverting amplifier

##### Analysis

Since the gain is assumed infinite, if  $V_o$  is finite then the input voltage must be zero. Hence

$$V_- = V_+ = V_i$$

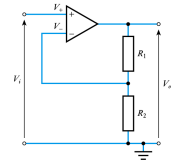
Since the input resistance of the op-amp is  $\infty$

$$V_- = V_o \frac{R_2}{R_1 + R_2}$$

and hence, since  $V_- = V_+ = V_i$

$$V_i = V_o \frac{R_2}{R_1 + R_2} \quad \text{and}$$

$$G = \frac{V_o}{V_i} = \frac{R_1 + R_2}{R_2}$$



### Basic operational amplifier circuits (contd.)

#### Example

Design a non-inverting amplifier with a gain of 25

From above  $G = \frac{V_o}{V_i} = \frac{R_1 + R_2}{R_2}$

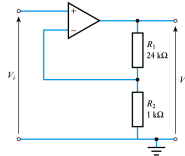
If  $G = 25$  then

$$\frac{R_1 + R_2}{R_2} = 25$$

$$R_1 + R_2 = 25R_2$$

$$R_1 = 24R_2$$

Therefore choose  $R_2 = 1 \text{ k}\Omega$  and  $R_1 = 24 \text{ k}\Omega$   
(choice of values will be discussed later)



### Basic operational amplifier circuits (contd.)

#### An inverting amplifier

##### Analysis

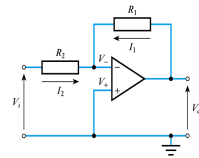
Since the gain is assumed infinite, if  $V_o$  is finite the input voltage must be zero. Hence

$$V_- = V_+ = 0$$

Since the input resistance of the op-amp is  $\infty$  its input current must be zero, and hence

$$I_1 = -I_2$$

$$\text{Now } I_1 = \frac{V_o - V_-}{R_1} = \frac{V_o - 0}{R_1} = \frac{V_o}{R_1} \quad I_2 = \frac{V_i - V_-}{R_2} = \frac{V_i - 0}{R_2} = \frac{V_i}{R_2}$$



### Basic operational amplifier circuits (contd.)

#### Analysis (continued)

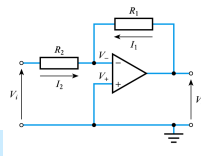
Therefore, since  $I_1 = -I_2$

$$\frac{V_o}{R_1} = -\frac{V_i}{R_2}$$

or, rearranging

$$G = \frac{V_o}{V_i} = -\frac{R_1}{R_2}$$

- Here  $V_-$  is held at zero volts by the operation of the circuit, hence the circuit is known as a **virtual earth circuit**



### Basic operational amplifier circuits (contd.)

#### Example

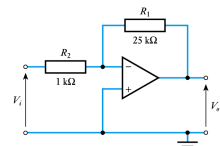
Design an inverting amplifier with a gain of -25

From above

$$G = \frac{V_o}{V_i} = -\frac{R_1}{R_2}$$

If  $G = -25$  then  $-\frac{R_1}{R_2} = -25$   
 $R_1 = 25R_2$

Therefore choose  $R_2 = 1 \text{ k}\Omega$  and  $R_1 = 25 \text{ k}\Omega$   
(we will consider the choice of values later)



## Other useful circuits

- In addition to simple amplifiers, op-amps can also be used in a range of other circuit
- The next few slides show a few examples of op-amp circuits for a range of purposes
- The analysis of these circuits is similar to that of the non-inverting and inverting amplifiers but (in most cases) this is *not* included here
- For more details of these circuits see the relevant section of the course text (as shown on the slides)

## Other useful circuits (contd.)

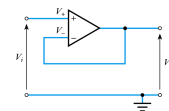
### • A unity gain buffer amplifier

#### Analysis

This is a special case of the non-inverting amplifier with  $R_1 = 0$  and  $R_2 = \infty$

Hence

$$G = \frac{R_1 + R_2}{R_2} = \frac{R_1}{R_2} + 1 = \frac{0}{\infty} + 1 = 1$$

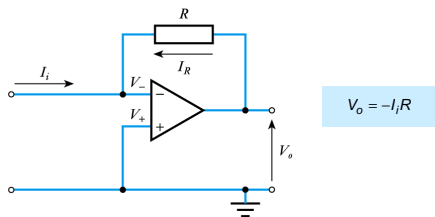


Thus the circuit has a gain of unity

- At first sight this might not seem like a very useful circuit, however, it has a high input resistance and a low output resistance and is therefore useful as a **buffer amplifier**

## Other useful circuits (contd.)

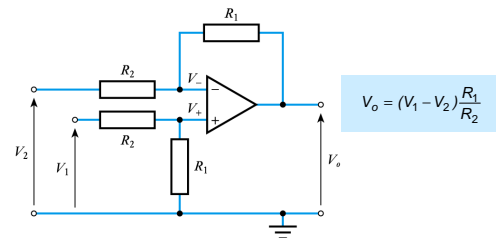
### • A current to voltage converter



$$V_o = -I_i R$$

## Other useful circuits (contd.)

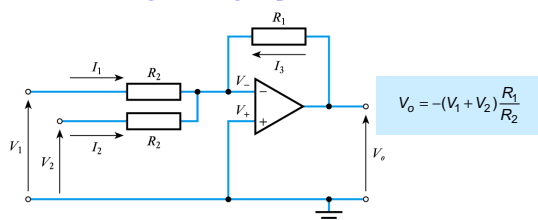
### • A differential amplifier (or subtractor)



$$V_o = (V_1 - V_2) \frac{R_1}{R_2}$$

## Other useful circuits (contd.)

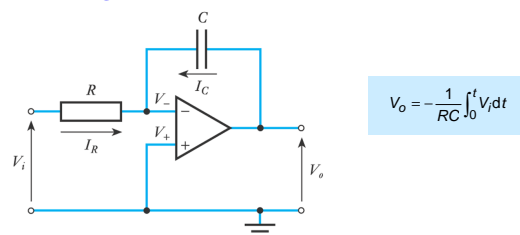
### • An inverting summing amplifier



$$V_o = -(V_1 + V_2) \frac{R_1}{R_2}$$

## Other useful circuits (contd.)

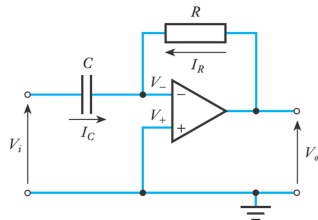
### • An integrator



$$V_o = -\frac{1}{RC} \int_0^t V_i dt$$

## Other useful circuits (contd.)

- A differentiator



$$V_o = -RC \frac{dV_i}{dt}$$

## Real operational amplifiers

- So far we have assumed the use of **ideal op-amps**
  - these have  $A_v = \infty$ ,  $R_i = \infty$  and  $R_o = 0$
- Real components do not have these ideal characteristics (though in many cases they approximate to them)
- In this section we will look at the characteristics of typical devices
  - perhaps the most widely used general purpose op-amp is the 741

## Real operational amplifiers (contd.)

- **Voltage gain**
  - typical gain of an operational amplifier might be 100 – 140 dB (voltage gain of  $10^5 - 10^6$ )
  - 741 has a *typical* gain of 106 dB ( $2 \times 10^5$ )
  - high gain devices might have a gain of 160 dB ( $10^8$ )
  - while not infinite, the gain of most op-amps is 'high-enough'
  - however, gain varies between devices and with temperature

## Real operational amplifiers (contd.)

- **Input resistance**
  - typical input resistance of a 741 is 2 M $\Omega$
  - very variable, for a 741 it can be as low as 300 k $\Omega$
  - the above value is typical for devices based on **bipolar transistors**
  - op-amps based on **field-effect transistors** generally have a much higher input resistance – perhaps  $10^{12} \Omega$
  - we will discuss bipolar and field-effect transistors later

## Real operational amplifiers (contd.)

- **Output resistance**
  - typical output resistance of a 741 is 75  $\Omega$
  - again very variable
  - often of more importance, is the maximum output current
  - the 741 will supply 20 mA
  - high-power devices may supply an amp or more

## Real operational amplifiers (contd.)

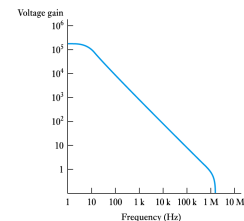
- **Supply voltage range**
  - a typical arrangement would use supply voltages of +15 V and – 15 V, but a wide range of supply voltages is usually possible
  - the 741 can use voltages in the range  $\pm 5$  to  $\pm 18$  V
  - some devices allow voltages up to  $\pm 30$  V or more
  - others, designed for low voltages, may use  $\pm 1.5$  V
  - many op-amps permit single voltage supply operation, typically in the range 4 to 30 V

## Real operational amplifiers (contd.)

- **Common-mode rejection ratio**
  - an ideal op-amp would not respond to common-mode signals.
  - real amplifiers do respond to some extent
  - the common-mode rejection ratio (CMRR) is the ratio of the response produced by a differential-mode signal to that produced by a common-mode signal
  - typical values for CMRR might be in the range 80 to 120 dB
    - 741 has a CMRR of about 90 dB

## Real operational amplifiers (contd.)

- **Frequency response**
  - typical 741 frequency response is shown here
  - upper cut-off frequency is a few hertz
  - frequency range generally described by the **unity-gain bandwidth**
  - high-speed devices may operate up to several gigahertz



## Selecting component values

- Our analysis assumed the use of an ideal op-amp
- When using real components we need to ensure that our assumptions are valid
- In general this will be true if we:
  - limit the gain of our circuit to *much less* than the open-loop gain of our op-amp
  - choose external resistors that are *small* compared with the input resistance of the op-amp
  - choose external resistors that are *large* compared with the output resistance of the op-amp.
- Generally we use resistors in the range 1 to 100 k $\Omega$

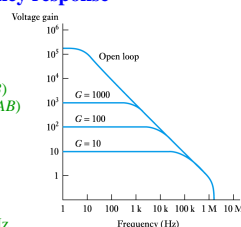
## Effects of feedback on op-amp circuits

- **Effects of feedback on the Gain**
  - negative feedback *reduces* gain from  $A$  to  $A/(1 + AB)$
  - in return for this loss of gain we get consistency, provided that the open-loop gain is much greater than the closed-loop gain (that is,  $A \gg 1/B$ )
  - using negative feedback, standard cookbook circuits can be used – greatly simplifying the design
  - these can be analysed without a detailed knowledge of the op-amp itself

## Effects of feedback on op-amp circuits (contd.)

- **Effects of feedback on frequency response**

- as the gain is *reduced* the bandwidth is *increased*
- gain  $\times$  bandwidth  $\approx$  constant
  - since gain is *reduced* by  $(1 + AB)$  bandwidth is *increased* by  $(1 + AB)$
- for a 741, gain  $\times$  bandwidth  $\approx 10^6$ 
  - if gain = 1000 BW  $\approx$  1000 Hz
  - if gain = 100 BW  $\approx$  10,000 Hz



## Effects of feedback on op-amp circuits (contd.)

- **Effects of feedback on input and output resistance**

- input/output resistance can be increased or decreased depending on how feedback is used.
  - we looked at this in an earlier lecture
  - in each case the resistance is changed by a factor of  $(1 + AB)$

### Example

- if an op-amp with a gain of  $2 \times 10^5$  is used to produce an amplifier with a gain of 100 then:

$$A = 2 \times 10^5$$

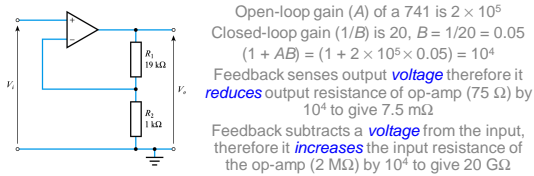
$$B = 1/G = 0.01$$

$$(1 + AB) = (1 + 2000) \approx 2000$$

### Effects of feedback on op-amp circuits (contd.)

- **Example**

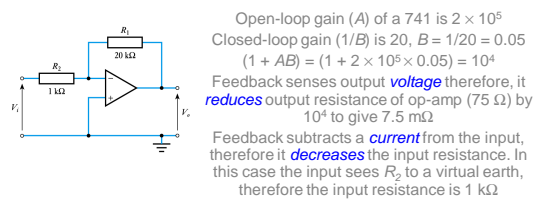
- determine the input and output resistance of the following circuit assuming op-amp is a 741



### Effects of feedback on op-amp circuits (contd.)

- **Example**

- determine the input and output resistance of the following circuit assuming op-amp is a 741



### Key points

- Operational amplifiers are among the most widely used building blocks in electronic circuits
- An *ideal* operational amplifier would have infinite voltage gain, infinite input resistance and zero output resistance
- Designers often make use of cookbook circuits
- Real op-amps have several non-ideal characteristics However, if we choose components appropriately this should not affect the operation of our circuits
- Feedback allows us to increase bandwidth by trading gain against bandwidth
- Feedback also allows us to alter other circuit characteristics

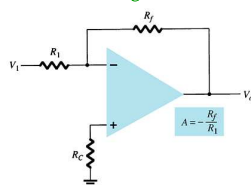
### Op-Amp Applications

Constant-gain multiplier  
 Voltage summing  
 Voltage buffer  
 Controlled sources  
 Instrumentation circuits  
 Active filters

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### Constant-Gain Amplifier

#### Inverting Version

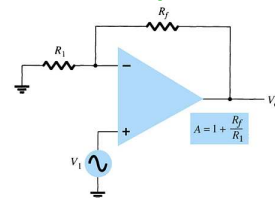


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### Constant-Gain Amplifier

#### Noninverting Version



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## Multiple-Stage Gains

The total gain (3-stages) is given by:

$$A = A_1 A_2 A_3$$

or

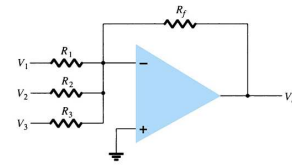
$$A = \left(1 + \frac{R_f}{R_1}\right) \left(-\frac{R_f}{R_2}\right) \left(-\frac{R_f}{R_3}\right)$$

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## Voltage Summing

The output is the sum of individual signals times the gain:

$$V_o = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right)$$



[Formula 14.3]

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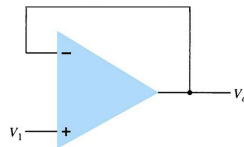
## Voltage Buffer

Any amplifier with no gain or loss is called a **unity gain amplifier**.

The advantages of using a unity gain amplifier:

- Very high input impedance
- Very low output impedance

Realistically these circuits are designed using equal resistors ( $R_1 = R_f$ ) to avoid problems with offset voltages.



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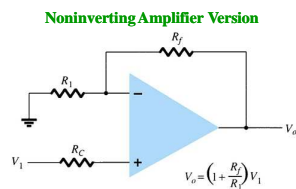
## Controlled Sources

Voltage-controlled voltage source  
Voltage-controlled current source  
Current-controlled voltage source  
Current-controlled current source

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## Voltage-Controlled Voltage Source

The output voltage is the gain times the input voltage. What makes an op-amp different from other amplifiers is its impedance characteristics and gain calculations that depend solely on external resistors.

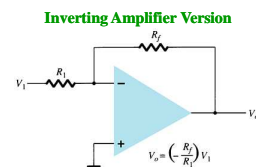


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## Voltage-Controlled Voltage Source

The output voltage is the gain times the input voltage. What makes an op-amp different from other amplifiers is its impedance characteristics and gain calculations that depend solely on external resistors.

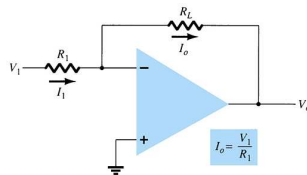


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## Voltage-Controlled Current Source

The output current is:

$$I_o = \frac{V_1}{R_1} = kV_1$$



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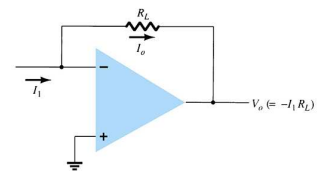
## Current-Controlled Voltage Source

This is simply another way of applying the op-amp operation. Whether the input is a current determined by  $V_{in}/R_1$  or as

$$I_1: \quad V_{out} = \frac{-R_f}{R_1} V_{in}$$

or

$$V_{out} = -I_1 R_L$$



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## Current-Controlled Current Source

This circuit may appear more complicated than the others but it is really the same thing.

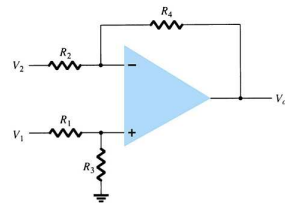
$$V_{out} = -\left(\frac{R_f}{R_{in}}\right) V_{in} \quad I_o = -\frac{V_{in}}{R_1 \parallel R_2}$$

$$\frac{V_{out}}{R_f} = -\frac{V_{in}}{R_1 \parallel R_2} \quad I_o = -V_{in} \left( \frac{R_1 + R_2}{R_1 \times R_2} \right)$$

$$\frac{V_{out}}{R_f} = -\frac{V_{in}}{R_{in}} \quad I_o = -\frac{V_{in}}{R_1} \left( \frac{R_1 + R_2}{R_2} \right)$$

$$I_o = -\left(1 + \frac{R_1}{R_2}\right) kI = kI$$

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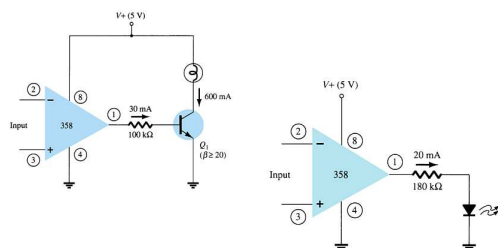
## Instrumentation Circuits

Some examples of instrumentation circuits using op-amps:

- Display driver
- Instrumentation amplifier

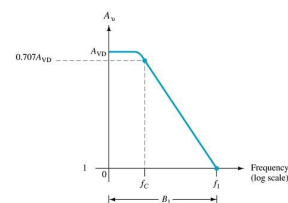
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## Display Driver



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## Instrumentation Amplifier



For all  $R_s$  at the same value (except  $R_p$ ):

$$V_o = \left(1 + \frac{2R}{R_p}\right) (V_1 - V_2) = k(V_1 - V_2)$$

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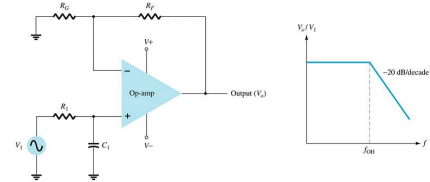
## Active Filters

Adding capacitors to op-amp circuits provides external control of the cutoff frequencies. The op-amp active filter provides controllable cutoff frequencies and controllable gain.

- Low-pass filter
- High-pass filter
- Bandpass filter

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## Low-Pass Filter—First-Order

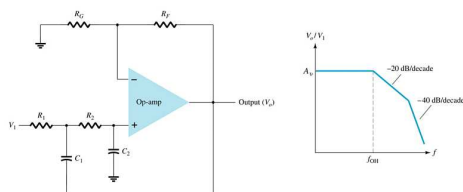


The upper cutoff frequency and voltage gain are given by:

$$f_{OH} = \frac{1}{2\pi R_1 C_1} \quad A_v = 1 + \frac{R_f}{R_1}$$

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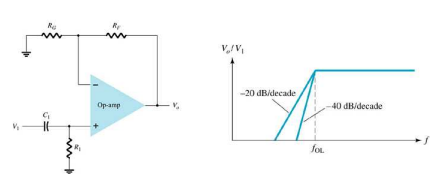
## Low-Pass Filter—Second-Order



The roll-off can be made steeper by adding more RC networks.

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## High-Pass Filter



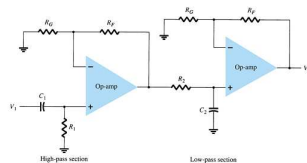
The cutoff frequency is determined by:

$$f_{OL} = \frac{1}{2\pi R_1 C_1}$$

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## Bandpass Filter

There are two cutoff frequencies: upper and lower. They can be calculated using the same low-pass cutoff and high-pass cutoff frequency formulas in the appropriate sections.



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